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Coordinates for a High Performance 4:1 Pressure Ratio Centrifugal Compressor

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Detroit Diesel Allison
Indianapolis, Indiana

July 1997

Prepared for
Lewis Research Center
Under Contract NAS3-23268



National Aeronautics and
Space Administration



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Final Report

by

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I. SUMMARY

The objective of the work conducted in this program was to define both aerodynamic and manufacturing design details for an advanced 4:1 pressure ratio single stage centrifugal compressor at a 10 lbm/sec flow size. The approach selected was to perform an exact aerodynamic scale of DDA's 404-III compressor from its design flow of 3.655 lbm/sec to the required 10 lbm/sec flow size.

Design tasks performed during this program included:

- o Aerodynamic design and analysis
- o Thermal analysis of the scaled impeller
- o Structural analysis of the scaled impeller including both static stress and vibration analyses.

The results of these tasks are reviewed in Sections II and III. Section IV presents a detailed manufacturing definition of the impeller blading and wheel geometry. The manufacturing definition includes a detail drawing of the impeller geometry and punched card description of both "hot" and "cold" impeller geometry.

II. AERODYNAMIC DESIGN AND ANALYSIS

The 4:1 Rc, 404-III single stage centrifugal compressor was designed in 1975 for use in an advanced regenerative gas turbine engine for truck/bus and power generation applications. The impeller design combined advanced aerodynamic features such as high back curvature (50°) and low blade loading with geometry completely compatible with production casting techniques. Goal compressor performance was achieved on the initial build and efficiency goals were exceeded by over 1% after one rematch. The design point total to static efficiency was 83.3% at a point with 8% minimum surge margin. This efficiency level is still the best total to static efficiency demonstrated in its flow class.

The flow size of the 404-III compressor is 3.655 lbm/sec at a mechanical speed of 36015 rpm. To scale the compressor to 10 lbm/sec, a 1.6529 scale factor must be applied to all linear dimensions. A true scale of this compressor would result in a diffuser exit radius of 16.306 inches. This radius exceeded current NASA rig constraints and, therefore, had to be reduced to 14.3 inches. A 90° annular bend was designed to direct the flow from the radial to the axial direction.

A complete meridional elevation of the scaled compressor is shown in Figure 1. The defined geometry is for the "hot running" condition with no impeller to shroud clearance adjustment. The original 404-III compressor was tested with a smooth approach inlet bell and rotating spinner. These contours are shown in Figure 1 and specifically defined in Table I.

The impeller consists of 15 full blades and 15 splitters. "Hot" flow path contours, tangential thickness distributions and polar coordinate definition of the blade meanline are presented for the hub and shroud contours in Tables II and III. Table II presents full blade definition while Table III gives the splitter geometry. The blade surface elements are constructed linear from hub to shroud along the defined quasi-normals. The coordinates given in Tables II

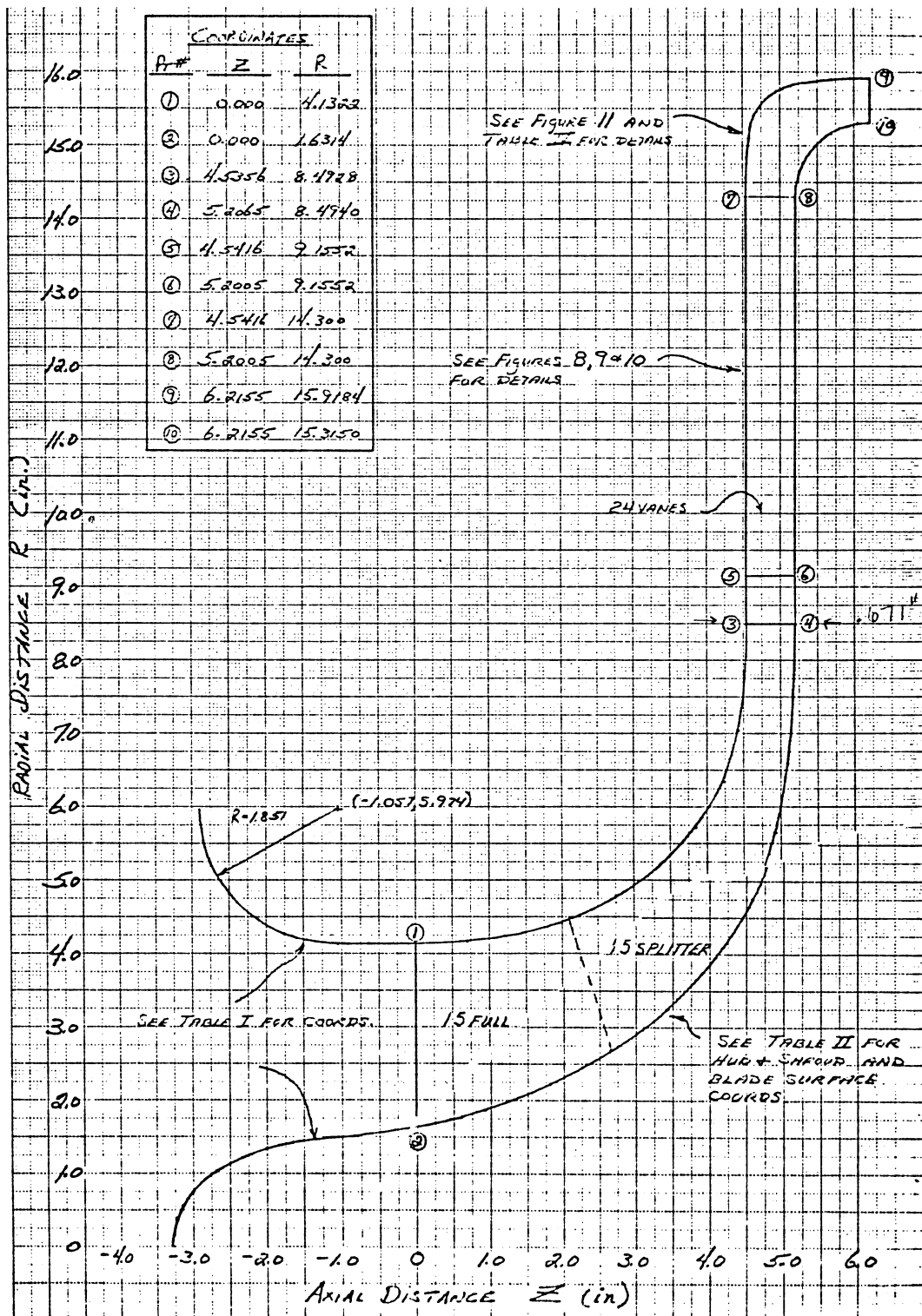


Figure 1. Meridional Flowpath for Scaled Impeller.

TABLE I. INLET BELL AND SPINNER CONTOUR COORDINATES.

INLET BELL: CIRCULAR ARC WITH CENTER AT (-1.057,5.974)

COORDINATES:

AXIAL LOCATION	RADIAL LOCATION
-2.908	5.974
-2.850	5.513
-2.750	5.225
-2.500	4.814
-2.250	4.558
-2.000	4.381
-1.750	4.257
-1.500	4.177
-1.057	4.123
-0.050	4.128
0.000	4.132

INLET SPINNER:

COORDINATES:

AXIAL LOCATION	RADIAL LOCATION
-3.3276	0.0000
-3.3111	0.1750
-3.2450	0.3886
-3.1623	0.5446
-2.9970	0.7564
-2.8317	0.9091
-2.6665	1.0293
-2.3359	1.2093
-2.0053	1.3344
-1.6747	1.4192
-1.3441	1.4711
-1.3000	1.4757
-1.0000	1.5000
-0.5000	1.5600
0.0000	1.6314

and III are for the impeller in the "hot and running" condition. A detailed description of the manufacturing or "cold" geometry is presented in Section IV.

Using data from the BU257 rig test of the 404-III compressor as a guide to impeller blockage and efficiency levels, a streamline curvature intrablade aerodynamic analysis was performed for the defined scaled compressor geometry. The aerodynamic analysis was conducted at design speed with the following input variables:

TABLE II. SCALED 404-III IMPELLER COORDINATES - HOT BLADE.
MEAN BLADE DEFINITION - FULL BLADE.

%M/MO	R HUB	Z HUB	R SHROUD	Z SHROUD	TIAN HUB	TIAN SHROUD	THETA HUB	THETA SHROUD
0.0000	1.6314	0.0003	4.1322	0.0	0.1328	0.0755	1.6331	0.0040
2.5000	1.6765	0.2352	4.1400	0.1795	0.1940	0.0930	7.0300	3.5643
5.0000	1.7309	0.4678	4.1486	0.3593	0.2174	0.1050	11.4915	6.8815
7.5000	1.7953	0.6982	4.1552	0.5396	0.2323	0.1136	15.2587	9.9100
10.0000	1.8673	0.9261	4.1679	0.7194	0.2413	0.1207	18.5542	12.7871
12.5000	1.9475	1.1516	4.1872	0.8988	0.2490	0.1243	21.6394	15.5122
15.0000	2.0339	1.3745	4.2114	1.0772	0.2541	0.1262	24.6302	18.0871
17.5000	2.1264	1.5951	4.2400	1.2544	0.2593	0.1256	26.6931	20.5941
20.0000	2.2250	1.8129	4.2744	1.4308	0.2642	0.1249	28.8285	22.7880
22.5000	2.3287	2.0287	4.3126	1.6083	0.2691	0.1230	30.9620	24.9620
25.0000	2.4402	2.2402	4.3561	1.7809	0.2733	0.1213	32.4163	27.0020
27.5000	2.5605	2.4469	4.4222	1.9455	0.2762	0.1199	33.9167	28.8420
30.0000	2.6860	2.6504	4.4881	2.1113	0.2794	0.1187	35.2751	30.6249
32.5000	2.8149	2.8521	4.5590	2.2805	0.2829	0.1177	36.5653	32.2831
35.0000	2.9519	3.0479	4.6342	2.4457	0.2861	0.1166	37.5653	33.8532
37.5000	3.0972	3.2383	4.7123	2.6062	0.2890	0.1153	38.5328	35.3323
40.0000	3.2504	3.4217	4.7972	2.7637	0.2917	0.1142	39.4325	36.7284
42.5000	3.4114	3.5991	4.8883	2.9186	0.2942	0.1136	40.2456	38.0392
45.0000	3.5802	3.7755	4.9875	3.0695	0.2966	0.1126	41.0284	39.2710
47.5000	3.7592	3.9272	5.0971	3.2170	0.2984	0.1108	41.7665	40.4073
50.0000	3.9451	4.0770	5.2104	3.3590	0.3006	0.1092	42.5027	41.4968
52.5000	4.1397	4.2164	5.3250	3.4958	0.3034	0.1073	43.2269	42.5366
55.0000	4.3397	4.3471	5.4478	3.6265	0.3057	0.1060	43.9687	43.5549
57.5000	4.5456	4.4694	5.5808	3.7523	0.3059	0.1054	44.7215	44.4739
60.0000	4.7562	4.5823	5.7178	3.8693	0.3086	0.1050	45.5049	45.4073
62.5000	4.9721	4.6858	5.8558	3.9783	0.3107	0.1054	46.3135	46.3430
65.0000	5.1918	4.7797	6.0039	4.0770	0.3132	0.1053	47.1628	47.2569
67.5000	5.4154	4.8657	6.1541	4.1653	0.3151	0.1041	48.0518	48.1387
70.0000	5.6427	4.9390	6.3021	4.2434	0.3195	0.1033	48.9848	49.0192
72.5000	5.8742	5.0077	6.4504	4.3077	0.3231	0.1027	49.9448	49.8786
75.0000	6.1088	5.0477	6.6003	4.3610	0.3289	0.1028	50.9720	50.7765
77.5000	6.3458	5.0775	6.7533	4.4013	0.3359	0.1042	52.0642	51.7155
80.0000	6.5837	5.1041	6.9032	4.4350	0.3436	0.1049	53.2221	52.6866
82.5000	6.8217	5.1279	7.0514	4.4613	0.3501	0.1047	54.4460	53.6902
85.0000	7.0600	5.1476	7.2022	4.4828	0.3589	0.1047	55.7350	54.7732
87.5000	7.2987	5.1632	7.3575	4.4988	0.3698	0.1049	57.0767	55.9385
90.0000	7.5375	5.1749	7.5159	4.5117	0.3828	0.1056	58.4677	58.0385
92.5000	7.7766	5.1800	7.6790	4.5212	0.3970	0.1068	60.0166	59.2839
95.0000	8.0157	5.1870	7.8423	4.5328	0.4150	0.1089	61.6370	59.6189
97.5000	8.2548	5.1958	8.0096	4.5433	0.4370	0.1115	63.3685	60.2613
100.0000	8.4940	5.2065	8.1828	4.5535	0.4629	0.1150	65.2113	62.0437

TABLE III. SCALED 404-III IMPELLER COORDINATES - HOT BLADE.
MEAN BLADE DEFINITION - SPLITTER.

%/MO	R HUB	Z HUB	R SHROUD	Z SHROUD	TTAN HUB	TTAN SHROUD	THETA HUB	THETA SHROUD
30.0000	2.6861	2.6506	4.4881	2.1113	0.1118	0.0359	34.3684	30.0904
31.5000	2.7755	2.7922	4.5375	2.2303	0.1401	0.0561	35.8393	31.3564
33.0000	2.8688	2.9311	4.5886	2.3471	0.1634	0.0746	35.7345	32.5645
35.0000	2.9659	3.0672	4.6408	2.4612	0.1802	0.0808	35.5435	33.7100
37.0000	3.0672	3.2003	4.6959	2.5739	0.1949	0.0863	37.2932	34.8066
38.5000	3.1728	3.3309	4.7537	2.6853	0.2068	0.0907	38.9734	35.8539
40.0000	3.2820	3.4579	4.8148	2.7950	0.2178	0.0948	39.6145	36.8528
42.0000	3.3945	3.5814	4.8783	2.9030	0.2280	0.0991	40.2088	37.7998
44.0000	3.5114	3.7007	4.9465	3.0092	0.2372	0.1023	40.7798	38.5660
45.0000	3.6330	3.8160	5.0206	3.1141	0.2452	0.1040	41.3325	39.5902
47.0000	3.7587	3.9267	5.0968	3.2155	0.2527	0.1052	41.8520	40.3902
49.0000	3.8887	4.0327	5.1749	3.3170	0.2597	0.1057	42.3604	41.1749
51.0000	4.0222	4.1339	5.2553	3.4145	0.2662	0.1060	42.8711	41.9288
52.0000	4.1592	4.2299	5.3357	3.5091	0.2721	0.1064	43.3815	42.6468
54.0000	4.2992	4.3217	5.4226	3.6009	0.2777	0.1063	43.8991	43.3441
56.0000	4.4416	4.4093	5.5142	3.6904	0.2829	0.1055	44.4210	44.0152
58.0000	4.5866	4.4924	5.6075	3.7750	0.2880	0.1050	44.9559	44.6767
59.0000	4.7346	4.5711	5.7015	3.8581	0.2928	0.1050	45.5017	45.3269
61.0000	4.8847	4.6452	5.7990	3.9356	0.2974	0.1050	46.0650	45.9707
63.0000	5.0374	4.7146	5.8989	4.0088	0.3019	0.1051	46.6448	46.6391
65.0000	5.1918	4.7797	6.0039	4.0770	0.3052	0.1050	47.2437	47.2860
66.0000	5.3472	4.8420	6.1147	4.1407	0.3105	0.1042	47.8614	47.8626
68.0000	5.5050	4.9040	6.2293	4.1984	0.3148	0.1036	48.4987	48.4860
70.0000	5.6556	4.9850	6.3488	4.2498	0.3178	0.1032	49.1525	49.1059
72.0000	5.8278	5.0496	6.4696	4.2955	0.3215	0.1030	49.8335	49.7321
73.0000	5.9919	5.0196	6.5923	4.3352	0.3256	0.1028	50.5335	50.3616
75.0000	6.1567	5.0491	6.7152	4.3696	0.3298	0.1029	51.2637	51.0029
77.0000	6.3225	5.0722	6.8377	4.3975	0.3337	0.1033	52.0213	51.6544
79.0000	6.4886	5.0931	6.9613	4.4223	0.3377	0.1037	52.8077	52.3204
80.0000	6.6551	5.1116	7.0858	4.4431	0.3409	0.1041	53.6197	52.9998
82.0000	6.8217	5.1280	7.2114	4.4613	0.3489	0.1043	54.4666	53.6955
84.0000	6.9885	5.1422	7.3381	4.4765	0.3557	0.1045	55.3461	54.4054
86.0000	7.1554	5.1544	7.4655	4.4895	0.3631	0.1047	56.2650	55.1356
87.0000	7.3225	5.1649	7.5938	4.5002	0.3712	0.1045	57.2224	55.8819
89.0000	7.4898	5.1729	7.7227	4.5093	0.3801	0.1053	58.2212	56.6562
91.0000	7.6572	5.1764	7.8507	4.5157	0.3896	0.1078	59.2581	57.4572
93.0000	7.8245	5.1812	7.9795	4.5229	0.4007	0.1099	60.2409	58.2926
94.0000	7.9917	5.1883	8.1095	4.5276	0.4127	0.1112	61.1578	59.1551
96.0000	8.1590	5.1949	8.2379	4.5313	0.4274	0.1125	62.0339	60.0318
98.0000	8.3266	5.2010	8.3654	4.5340	0.4440	0.1137	62.8393	61.0458
100.0000	8.4943	5.2066	8.4918	4.5356	0.4628	0.1150	63.5520	62.0458

- o Corrected flow = 10 lbm/sec
- o Corrected speed = 21789 rpm
- o Inlet pressure = 14.7 psia
- o Inlet temperature = 518.7°R

The resulting distributions of impeller relative velocity and blade loading distributions are shown plotted as a function of percent meridional distance in Figures 2 through 7.

The vane diffuser consists of 24 modified, two-dimensional wedge vanes with the leading edge located at a radius ratio of 1.0778 relative to the impeller exit. The diffuser entrance region is shown in Figure 8 and is centered on the impeller exit. The diffuser has an overall area ratio of 2.754 with a total divergence angle of 7.791°. The vane passage cross-section is presented in Figure 9 with an enlarged view of the leading edge shown in Figure 10. The individual vanes are constructed from straight line segments between points 1 and 2, Figure 9, for the pressure surface and between points 4 and 5 for a portion of the suction surface. The leading edge portion of the suction surface is formed by an arc as shown in Figure 10. The suction surface arc has a radius of curvature of 45.233 inches and is tangent to the leading edge circle at points 3 and to the straight line between points 4 and 5 at point 4. The diffuser exit radius is 14.30 inches and dumps directly into a 90° annular bend.

The annular bend is shown in Figure 11 with detailed coordinates presented in Table IV. Primary considerations in the design of the annular bend were:

- o Minimize static pressure gradients at the diffuser exit plane
- o Maintain maximum flowpath radius at 16.0 inches

To avoid large static pressure gradients at the diffuser exit, the annular bend was designed with a generous radius of curvature to gap ratio of 2.0. The area distribution shown in Figure 12 was selected to reduce velocity levels around the bend and, thereby, reduce total pressure losses.

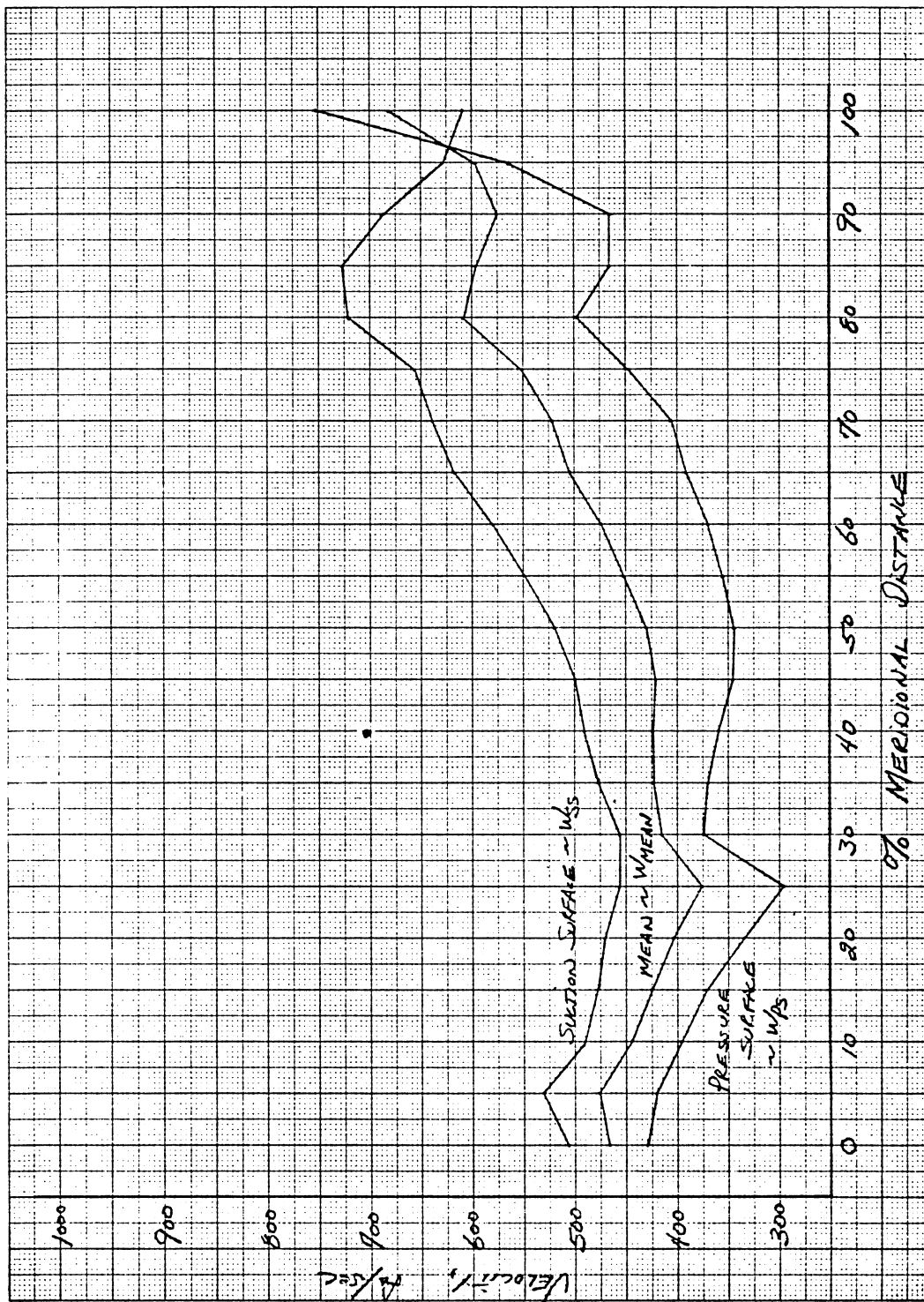


Figure 2. Impeller Hub Relative Velocity.

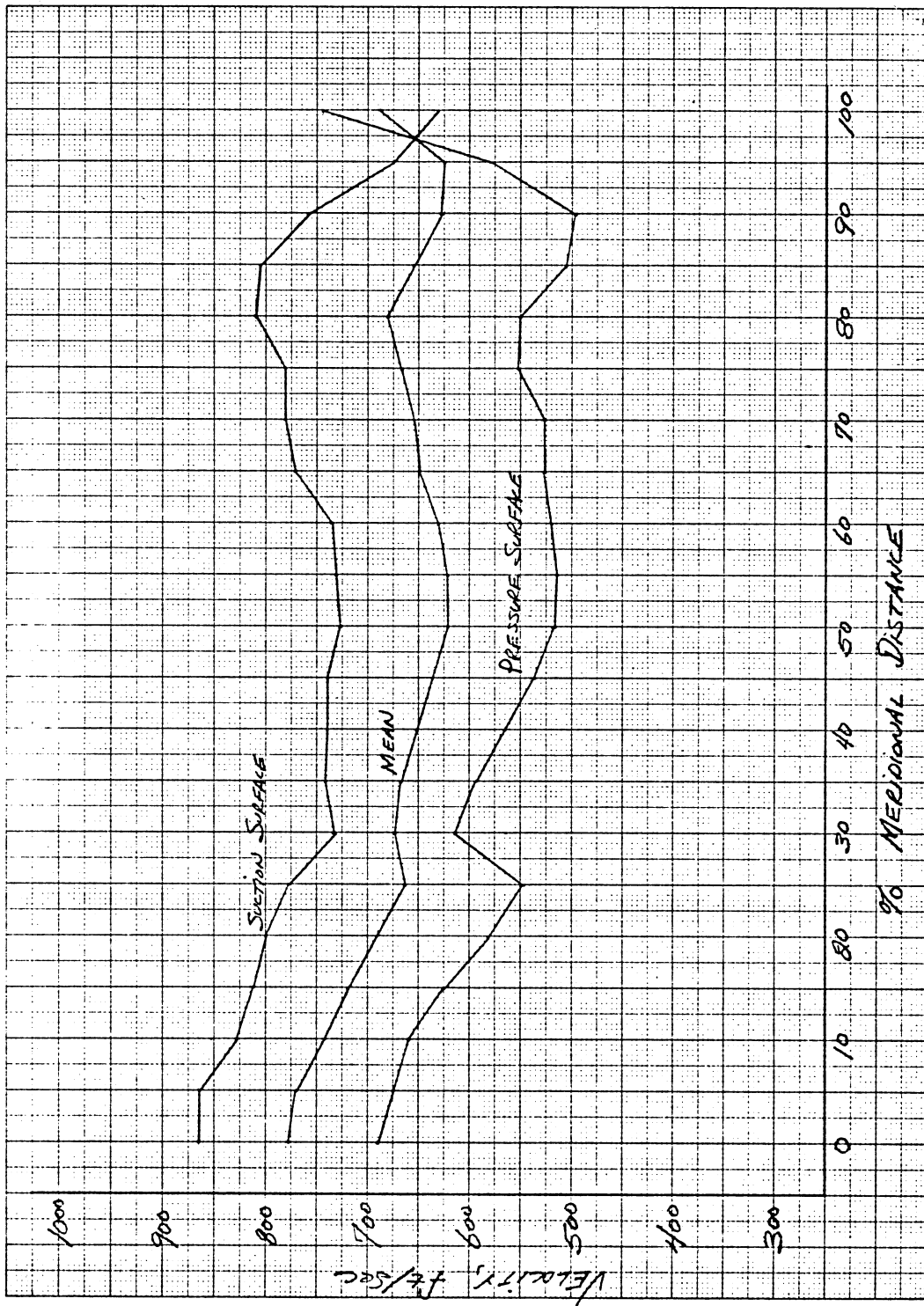


Figure 3. Impeller Mean Relative Velocity.

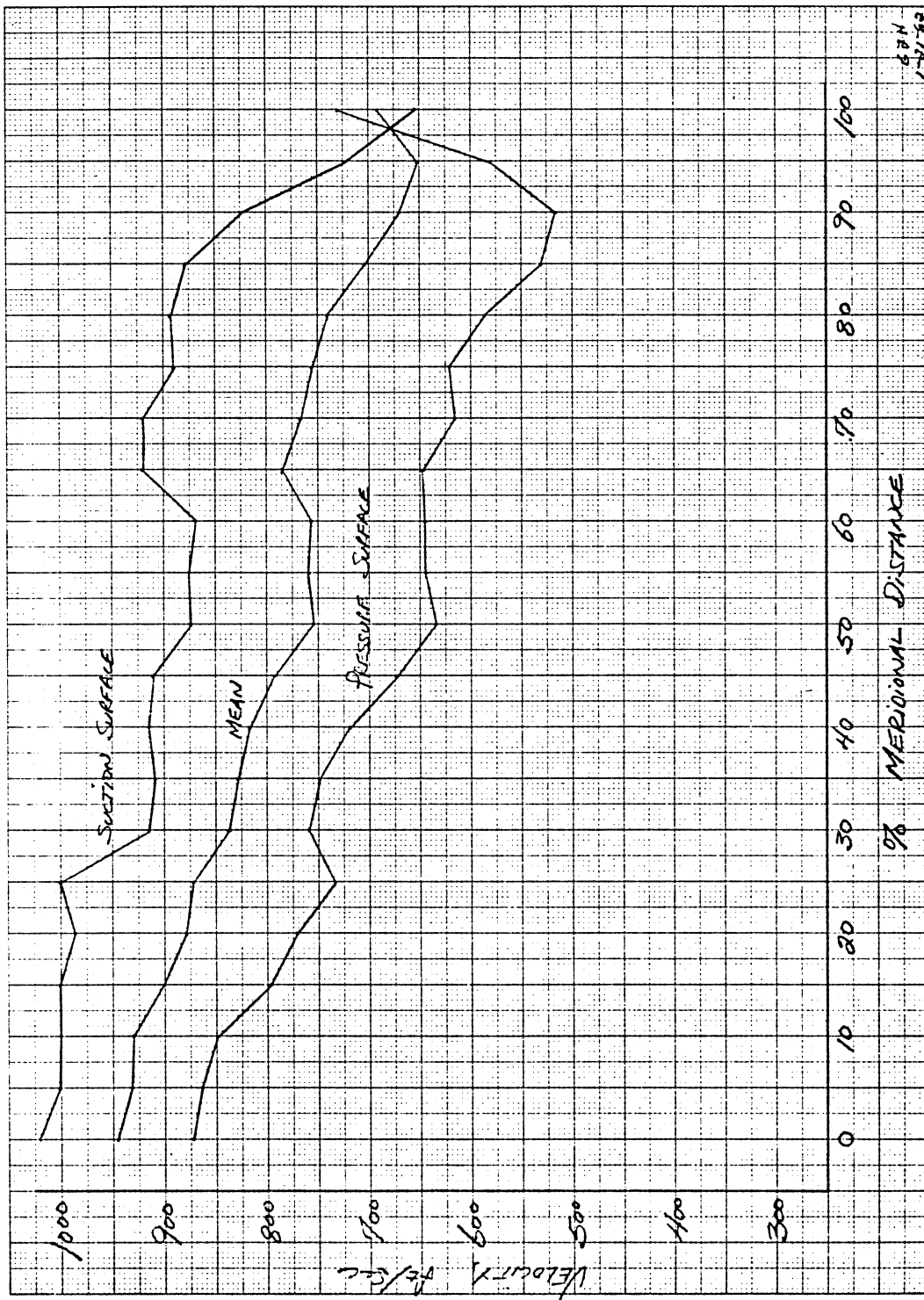


Figure 4. Impeller Tip Relative Velocity.

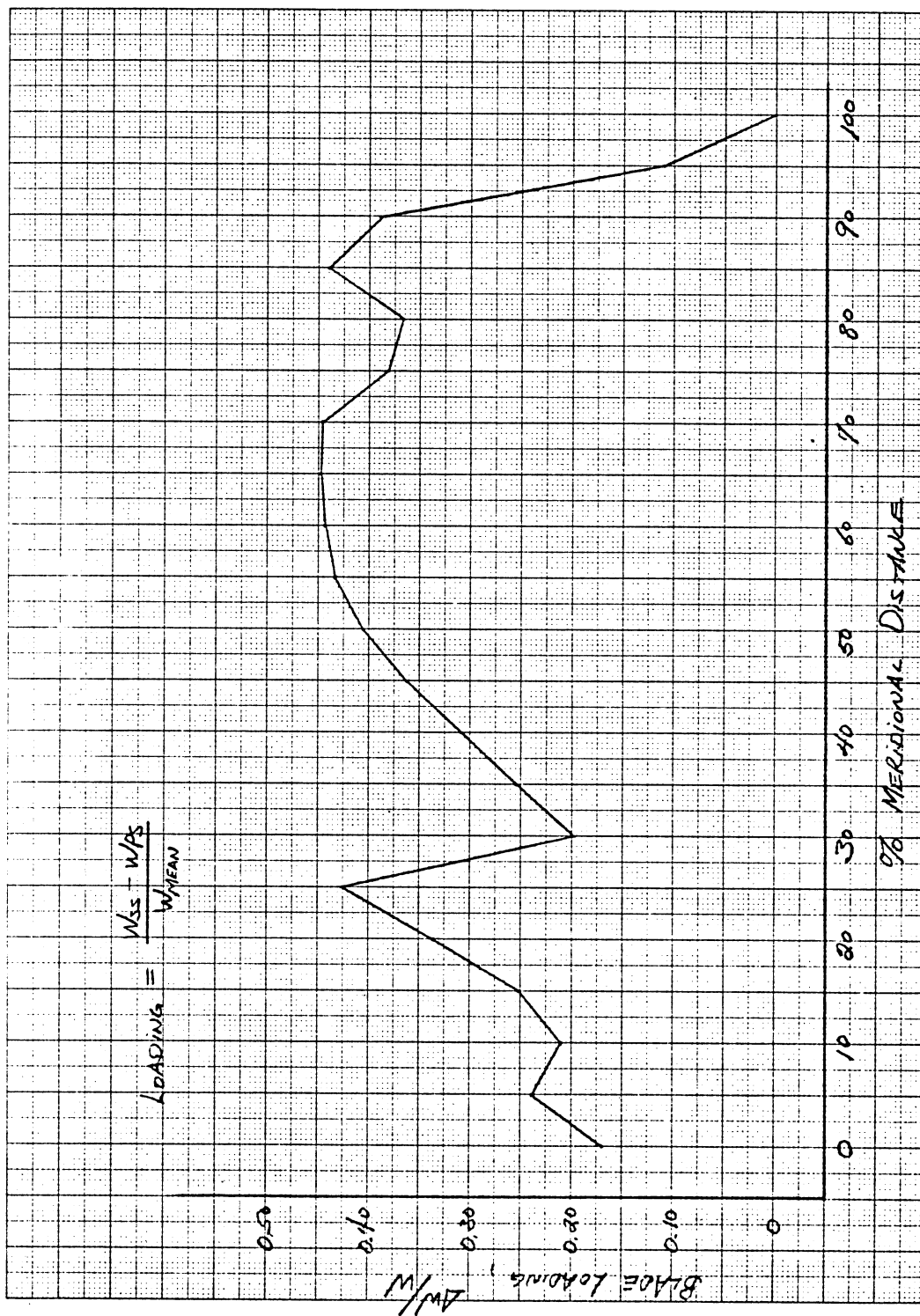


Figure 5. Impeller Hub Blade Loading.

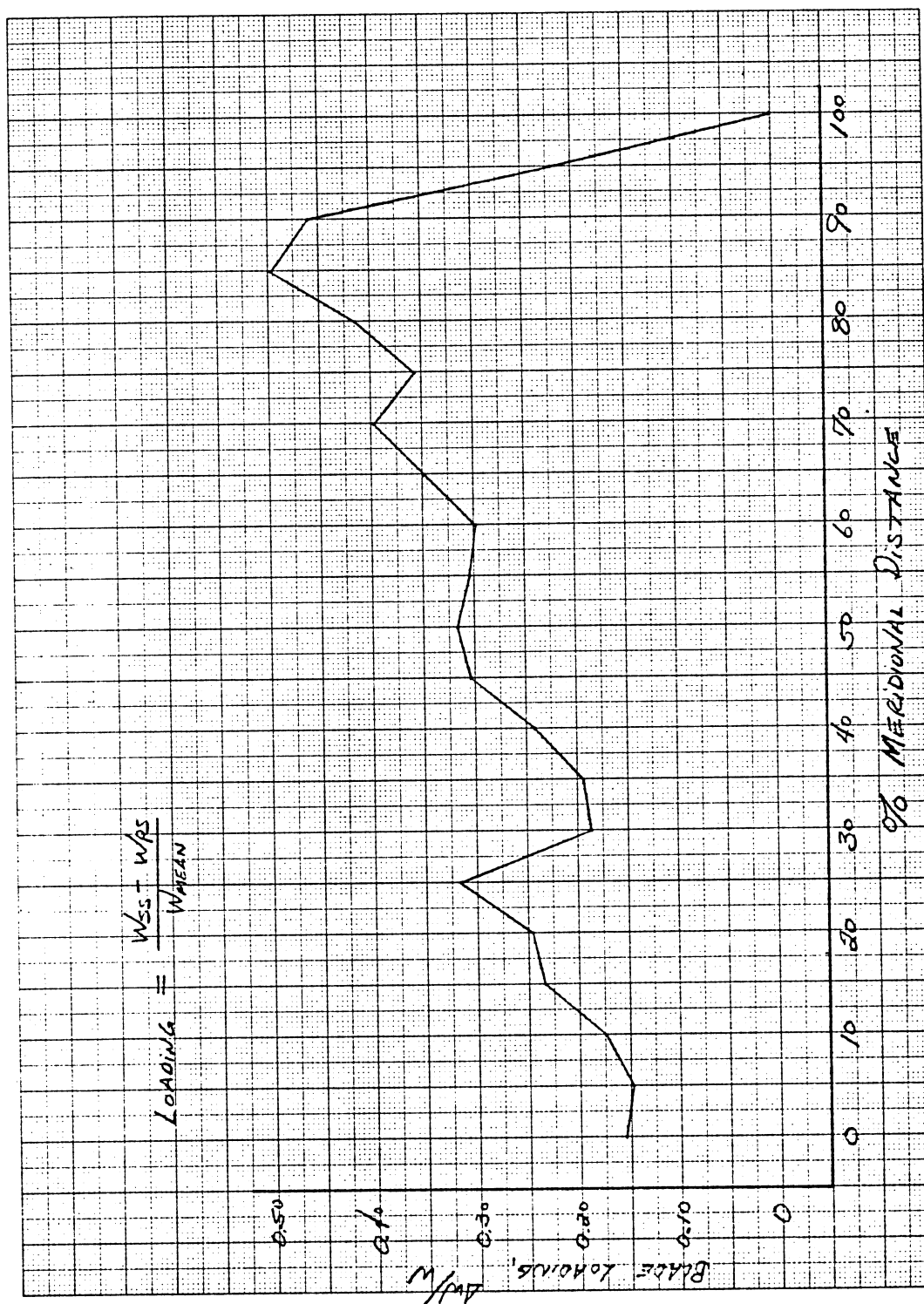


Figure 6. Impeller Mean Blade Loading.

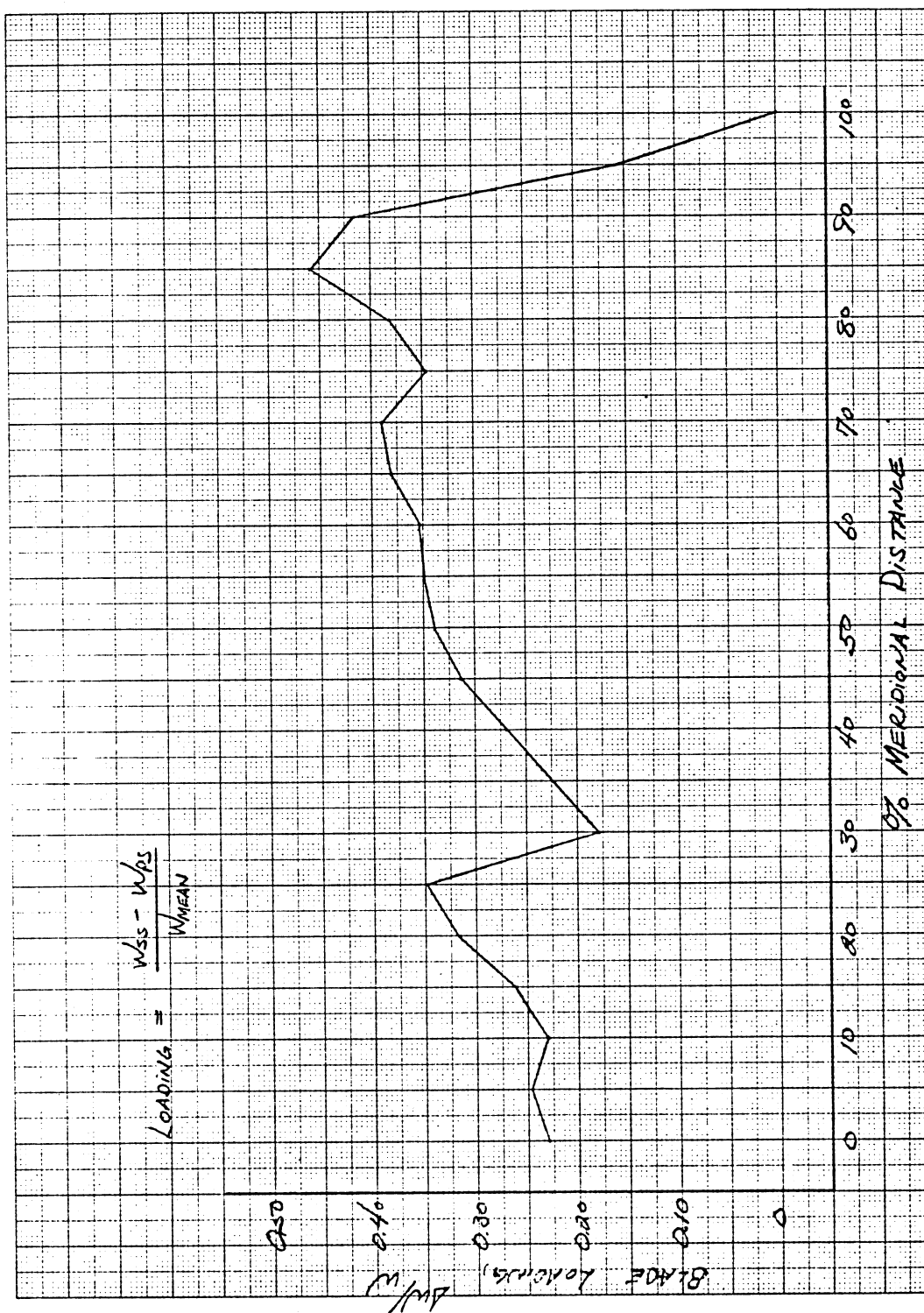
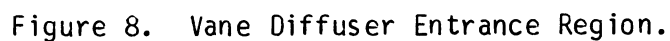


Figure 7. Impeller Tip Blade Loading.



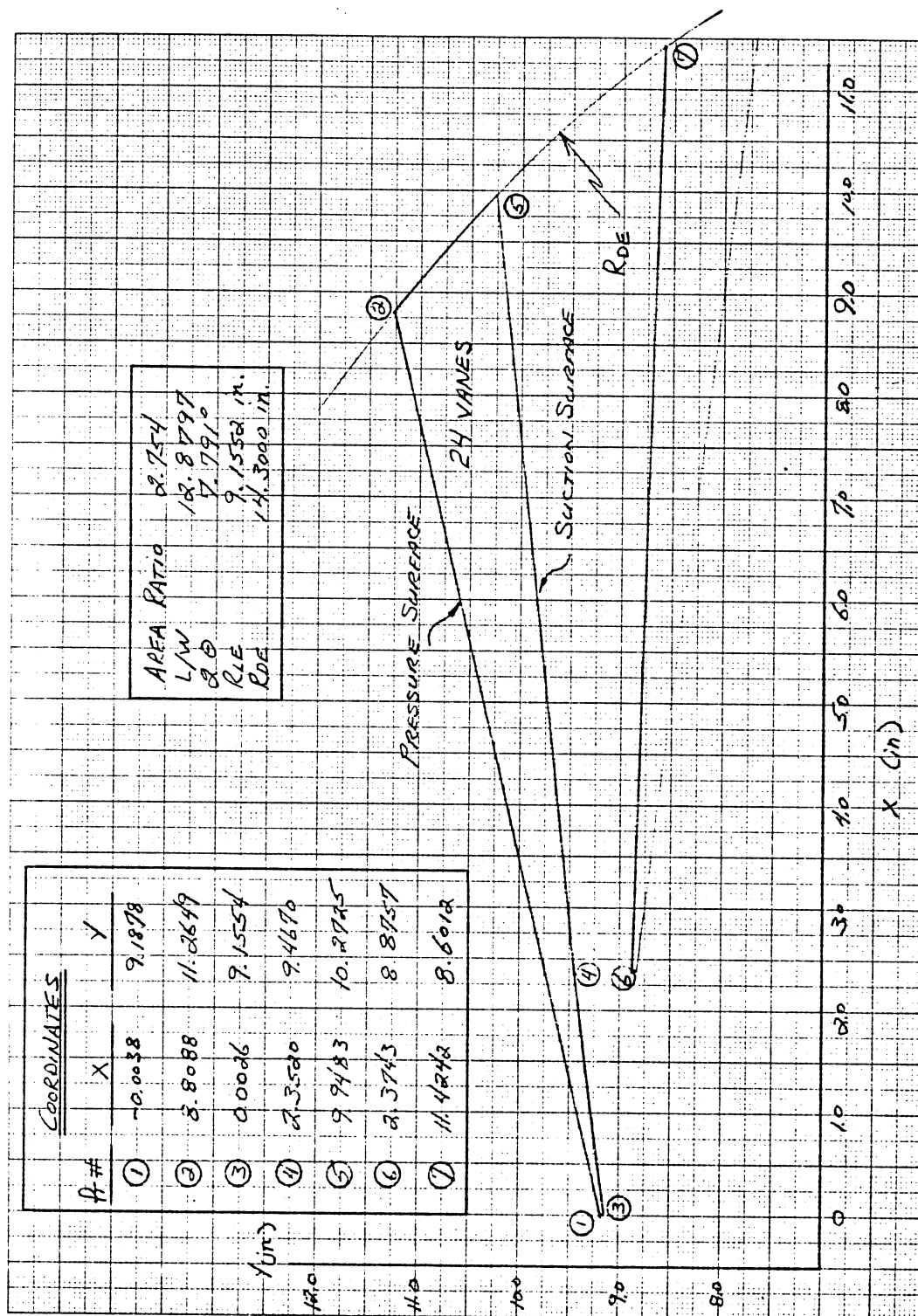


Figure 9. Diffuser Cross-section.

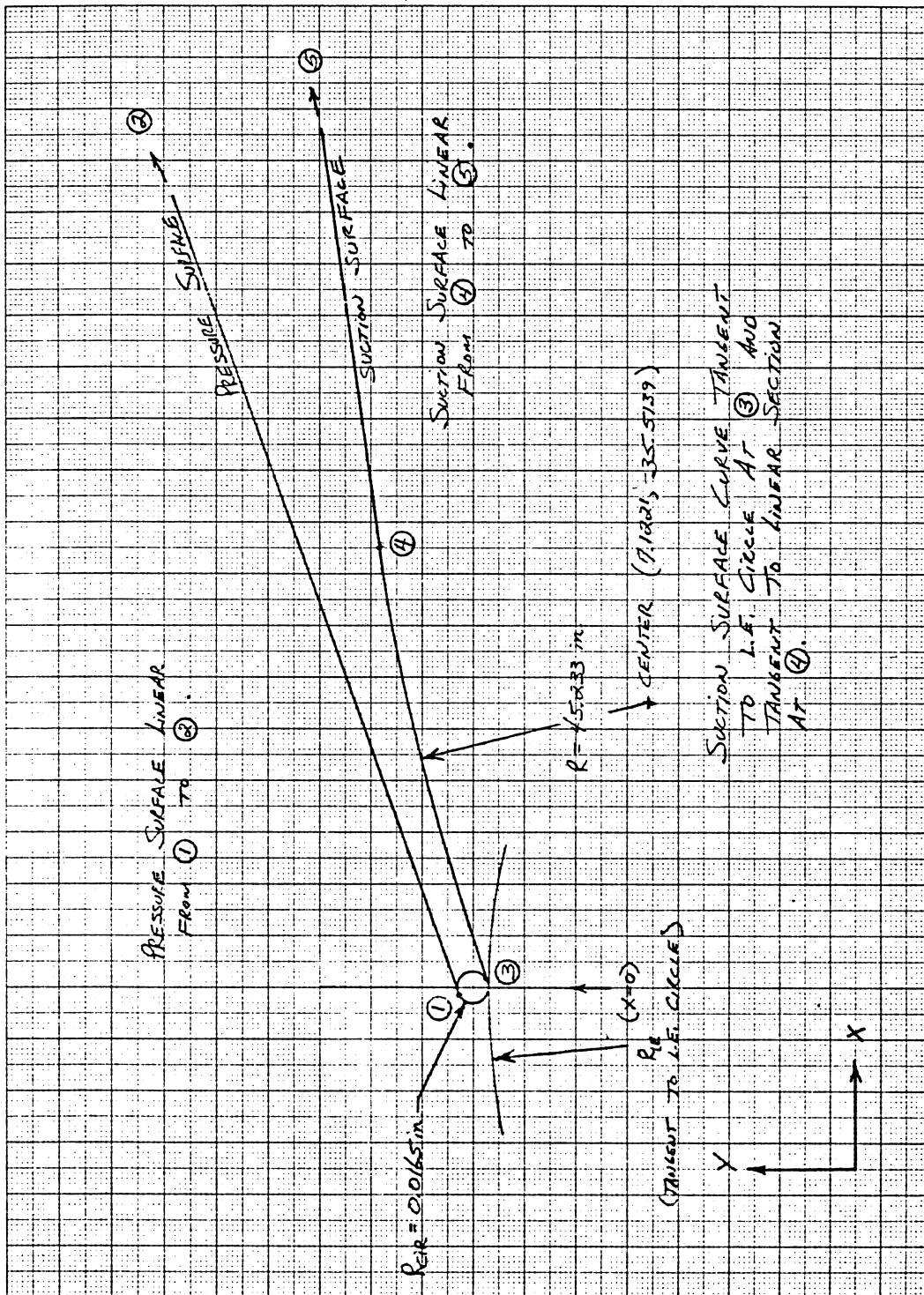


Figure 10. Leading Edge Region of Vane Diffuser.

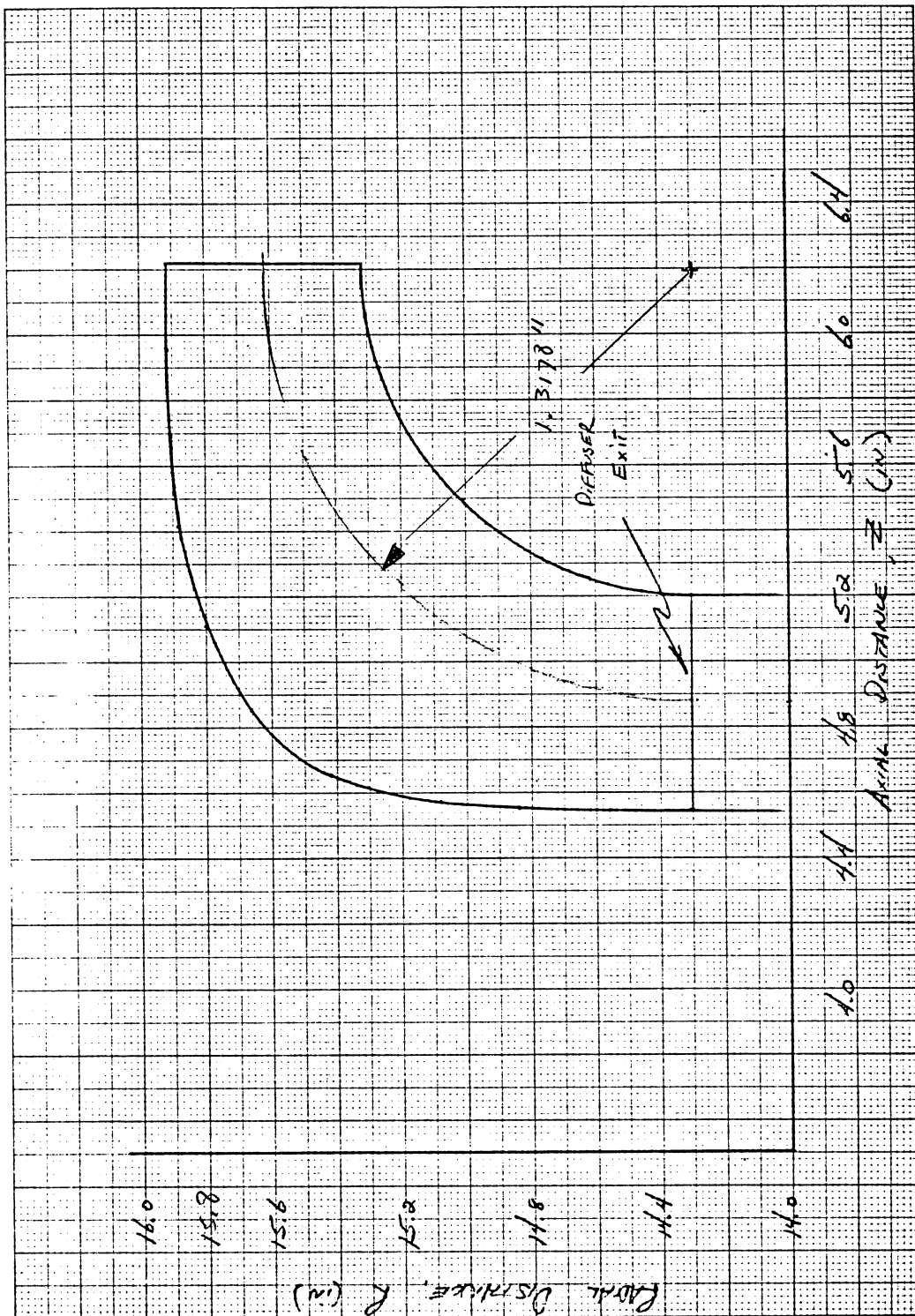


Figure 11. 90° Annular Bend.

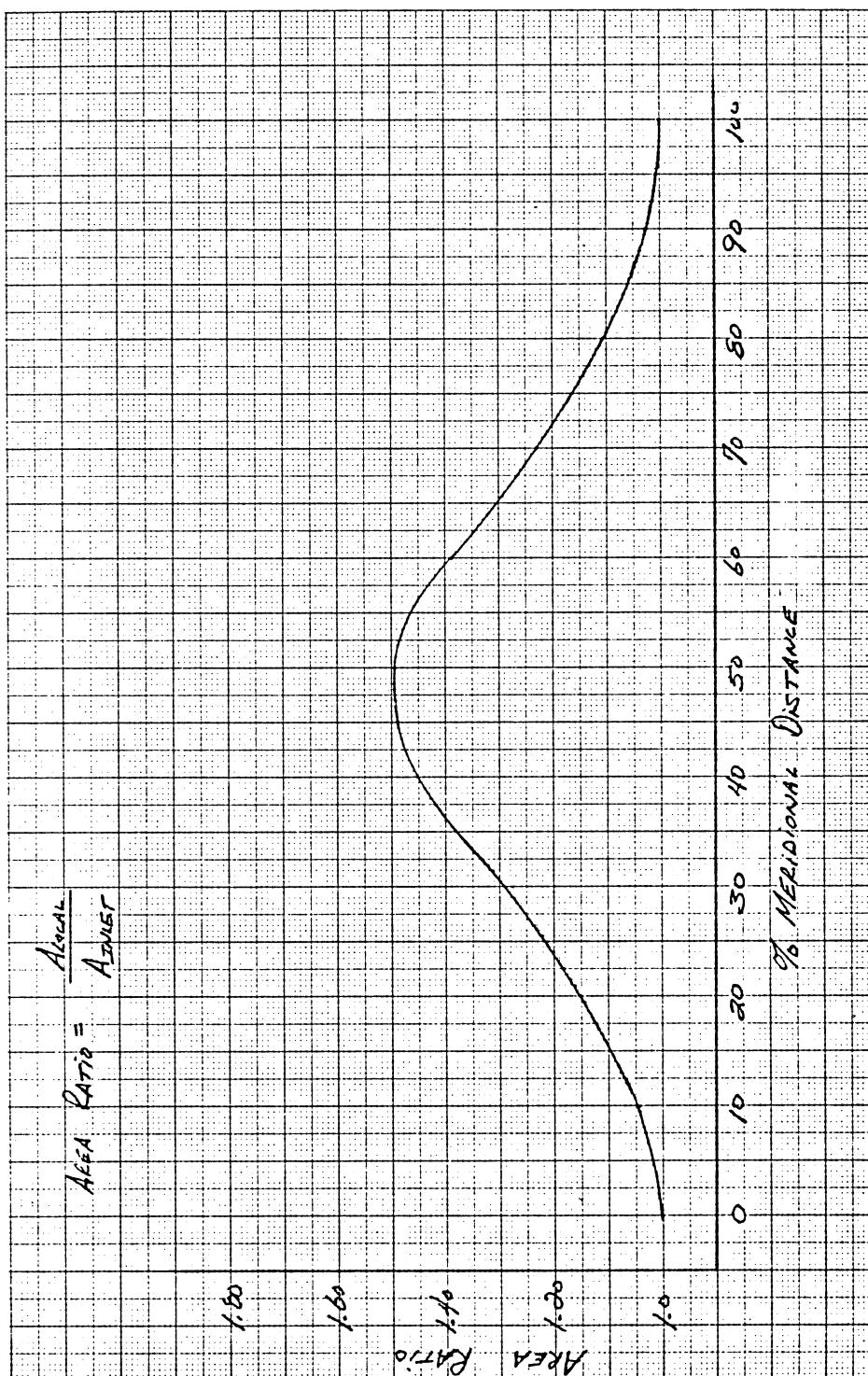


Figure 12. Area Distribution for 90° Annular Bend.

TABLE IV. ANNULAR BEND CONTOUR COORDINATES.

<u>%M/MO</u>	<u>R HUB</u>	<u>Z HUB</u>	<u>R SHROUD</u>	<u>Z SHROUD</u>	<u>AREA /AREA1</u>
0	14.3000	5.2005	14.3000	4.5416	1.0000
10	14.4588	5.2130	14.5600	4.5450	1.0404
20	14.6137	5.2502	14.8400	4.5500	1.1501
30	14.7608	5.3111	15.0840	4.5720	1.2775
40	14.8966	5.3943	15.4190	4.6580	1.4524
50	15.0177	5.4978	15.6670	4.8520	1.4911
60	15.1211	5.6189	15.8000	5.1150	1.3872
70	15.2044	5.7547	15.8680	5.4160	1.2285
80	15.2653	5.9018	15.9020	5.6930	1.1082
90	15.3025	6.0567	15.9150	5.9580	1.0277
100	15.3150	6.2155	15.9184	6.2155	1.0001

An estimated performance map was prepared for the scaled compressor stage and is given in Figure 13. Flow-speed and efficiency lapse rates were maintained similar to BU 257 data. However, allowance was made to overall efficiency levels to account for the geometrical changes, i.e. reduced area ratio diffuser and the 90° annular bend. In addition, Reynold's number effects were estimated from internal DDA procedures.

Impeller to shroud clearance distributions for both "build" and "hot running" conditions are presented for the 404-III impeller in Figure 14. Build clearances were deduced from design contours for the "cold" impeller and shroud in conjunction with "build" wax check measurements. "Hot running" clearances were developed from predicted design speed contours for the impeller and shroud and post test rub pin measurements. Scaled values of these clearances were assumed in the estimated map shown in Figure 13.

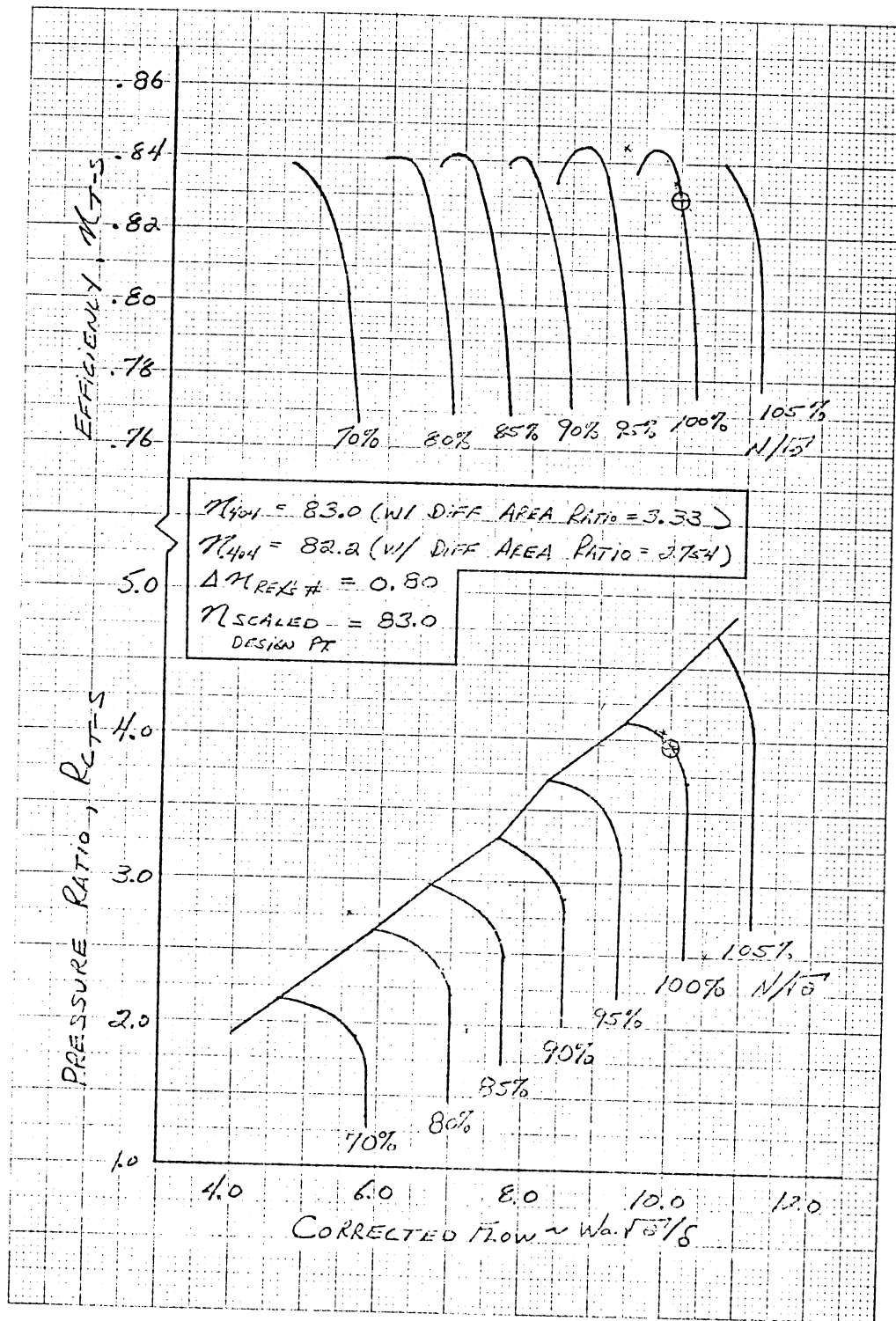


Figure 13. Estimated Performance Map for Scaled Compressor.

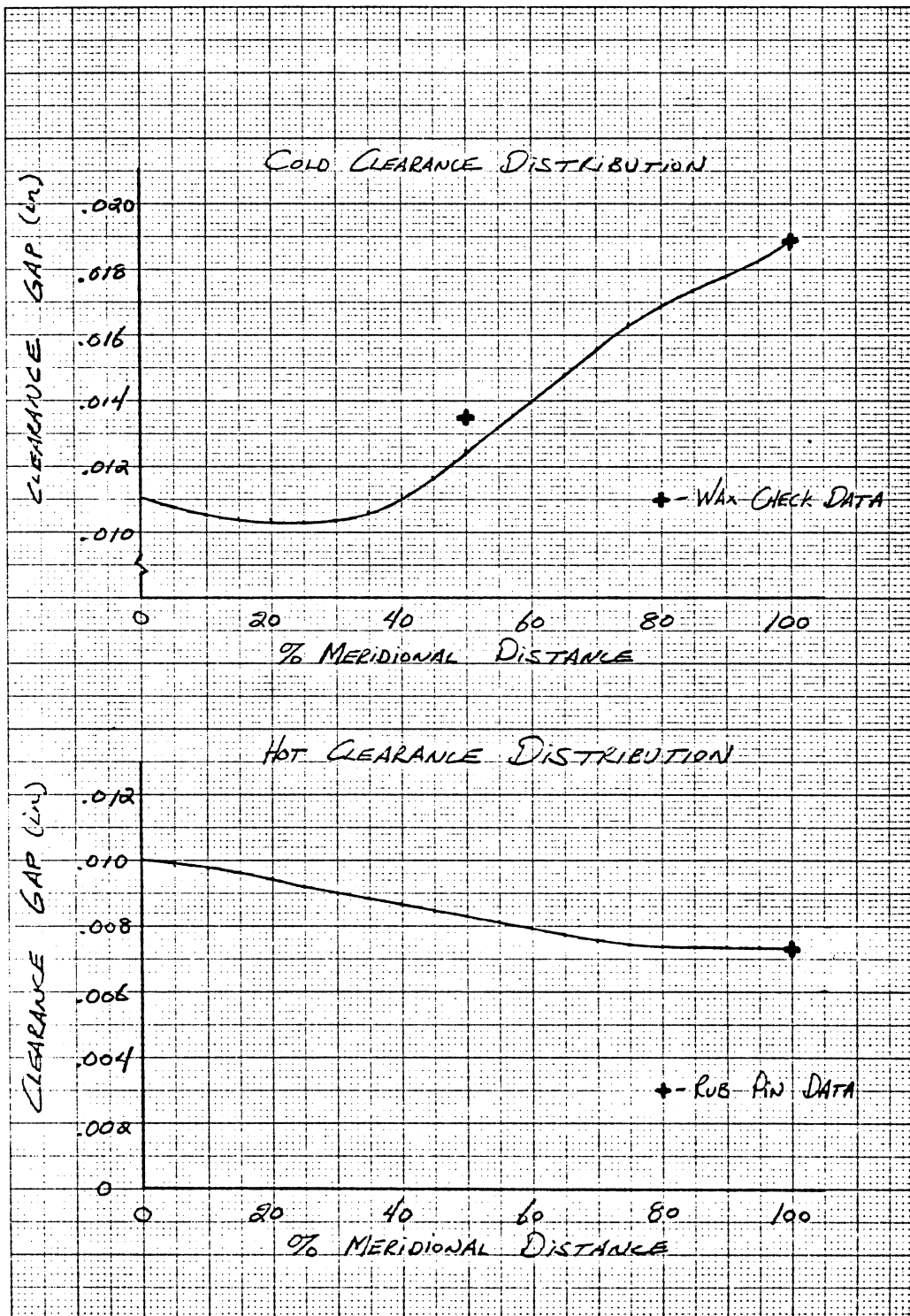


Figure 14. 404-III "hot" and "cold" Clearance Distributions.

III. STRUCTURAL ANALYSIS

A complete structural analysis was performed for the scaled impeller. The overall analysis was conducted for the defined aerodynamic geometry at a design speed of 21789 rpm and with standard day inlet conditions of 14.7 psia pressure and 518.7°R inlet temperature. The material properties were assumed to be those of Titanium 6AL4V. The overall structural analysis consisted of several individual but complementary tasks, namely:

- o Heat transfer
- o Static stress, and
- o Vibrational analyses.

The heat transfer analysis was required to provide temperature distributions for accurate determination of thermally induced stresses and deflections. Boundary conditions consisting of anticipated rig oil temperatures and back face seal leakage were obtained from NASA personnel and were included in the axisymmetric heat transfer analysis. Results of the heat transfer analysis are presented as isotherm lines on the defined scale compressor impeller geometry in Figure 15.

The static stress analysis consisted of several tasks:

- o Axisymmetric modeling of the complete wheel geometry
- o Evaluation of stresses from axisymmetric model in terms of low cycle fatigue and burst margins
- o Triangular plate modeling of the full blade, splitter and backplate
- o Evaluation of triangular plate results in terms of peak stress levels, high cycle fatigue and detailed deflection characteristics.

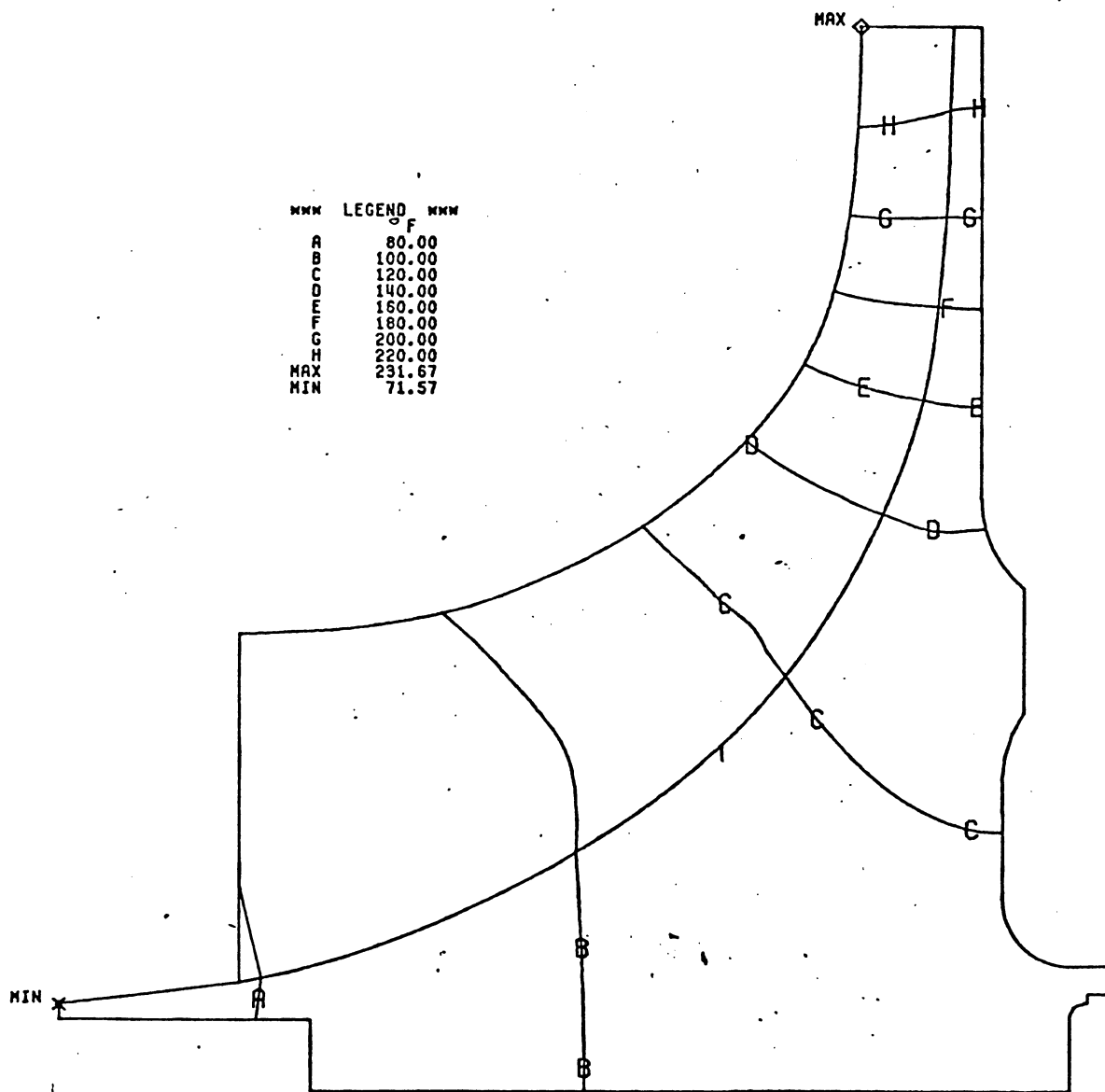


Figure 15. Temperature Distributions for Scaled Impeller.

Initially, the entire wheel was described with an axisymmetric finite element model. This model incorporated the isotherms from the heat transfer analysis, the desired wheel geometry (back face contouring and bore diameters) and flat radial plates to simulate the weight and approximate stiffness of the impeller blading.

The axisymmetric finite element model for the scaled impeller geometry is shown in Figure 16. Resulting distributions of design speed equivalent, axial, radial and tangential stresses are presented in Figures 17, 18, 19 and 20. The analysis did not include an axial clamp load which would result from tie bolt stretching. In order to evaluate the possible effects of a given axial load on stress levels and distribution, an arbitrarily assumed 10,000 lb load (typical of 404-III loads) was then applied at the curvic coupling location. The effects of this load are minimal as shown in Figure 21.

The locations of peak stress were identified and used in a low cycle fatigue and burst speed analysis. The results of these analyses are summarized in Figure 22 with the highest stresses occurring in the bore. Material properties used in the low cycle fatigue analysis are given in Figure 23. As evident from the peak stresses of Figure 22 and the properties of Figure 23, stress levels were such that lives well in excess of 10^6 cycles are projected. Burst speeds were calculated to be 182% of design speed based on an average radial stress and 199% speed based on average tangential stress.

Using deflections from the axisymmetric wheel analysis as boundary conditions, a triangular plate model was constructed for the full blade, splitter and backplate. The full blade model is shown in Figure 24. Figures 25, 26, 27 and 28 present the results for maximum principal and Von Mises equivalent stresses for the full blade pressure and suction surfaces. The same data is provided for the splitter in Figures 29 through 33. A segment of the backplate was analyzed to evaluate blade/backplate interaction effects. The backplate model is presented in Figure 34 with maximum principal and Von Mises equivalent stresses given in Figures 35 through 38.

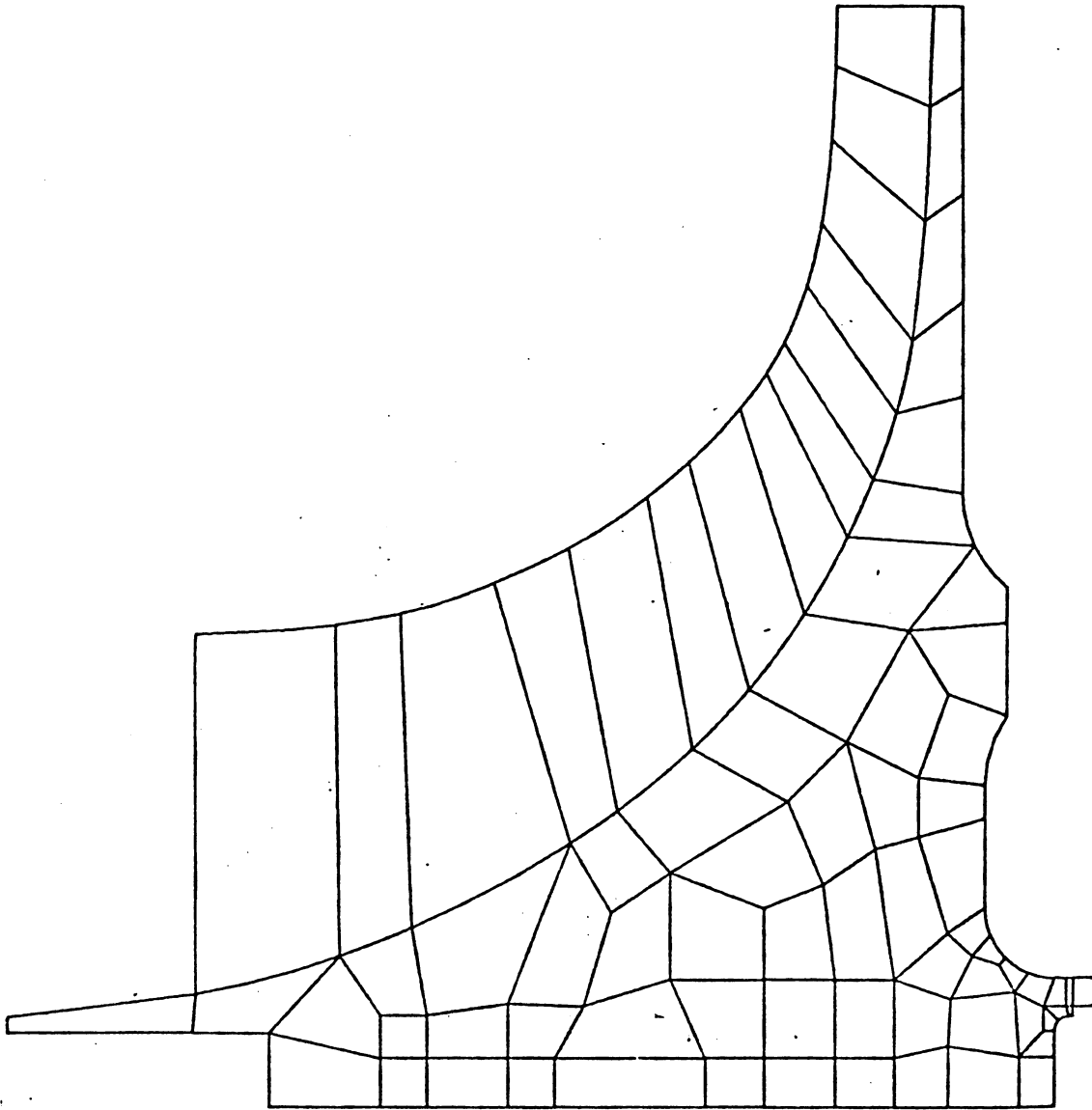


Figure 16. Axisymmetric Stress Model for Scaled Impeller.

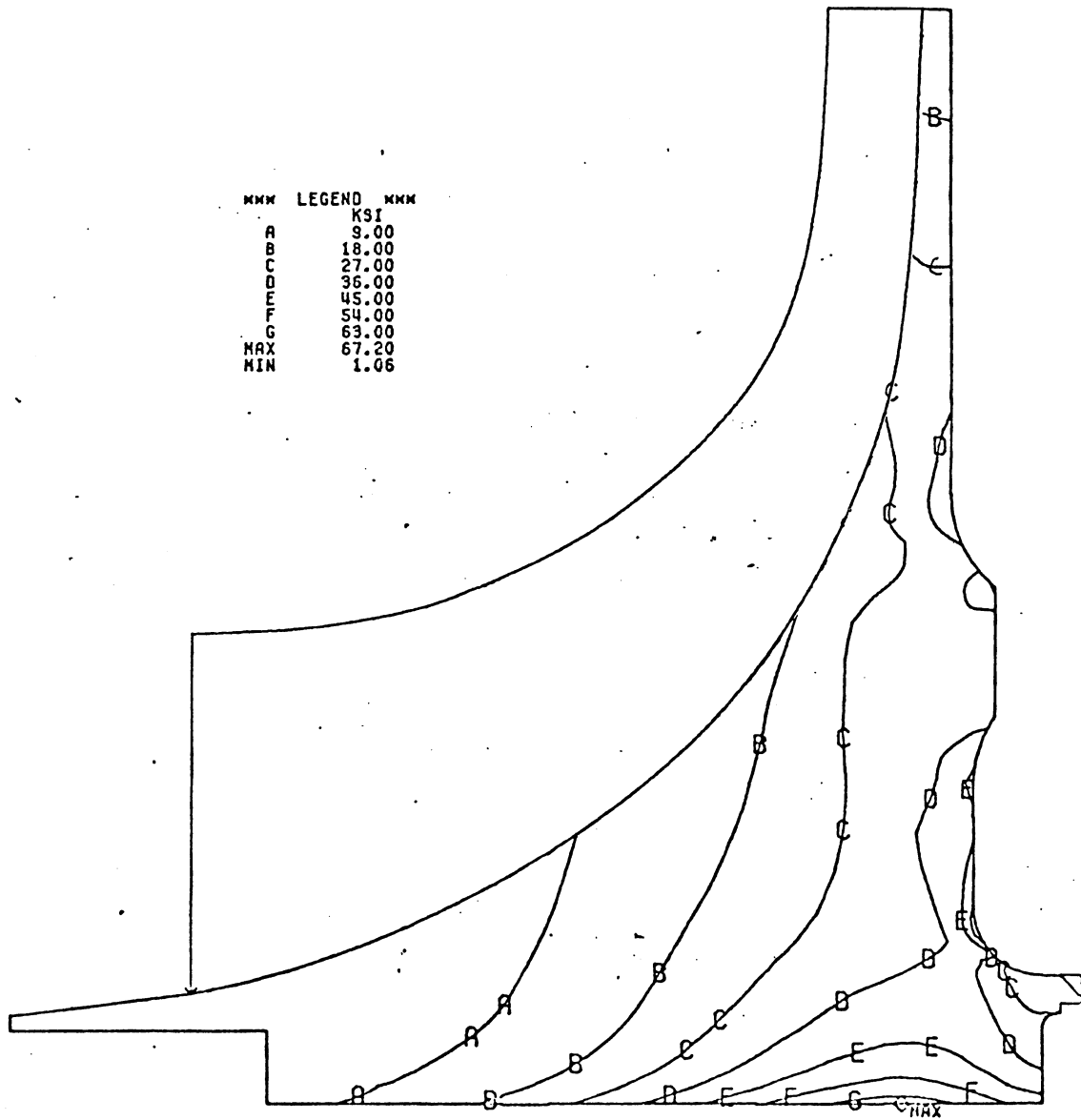


Figure 17. Impeller Equivalent Stresses.

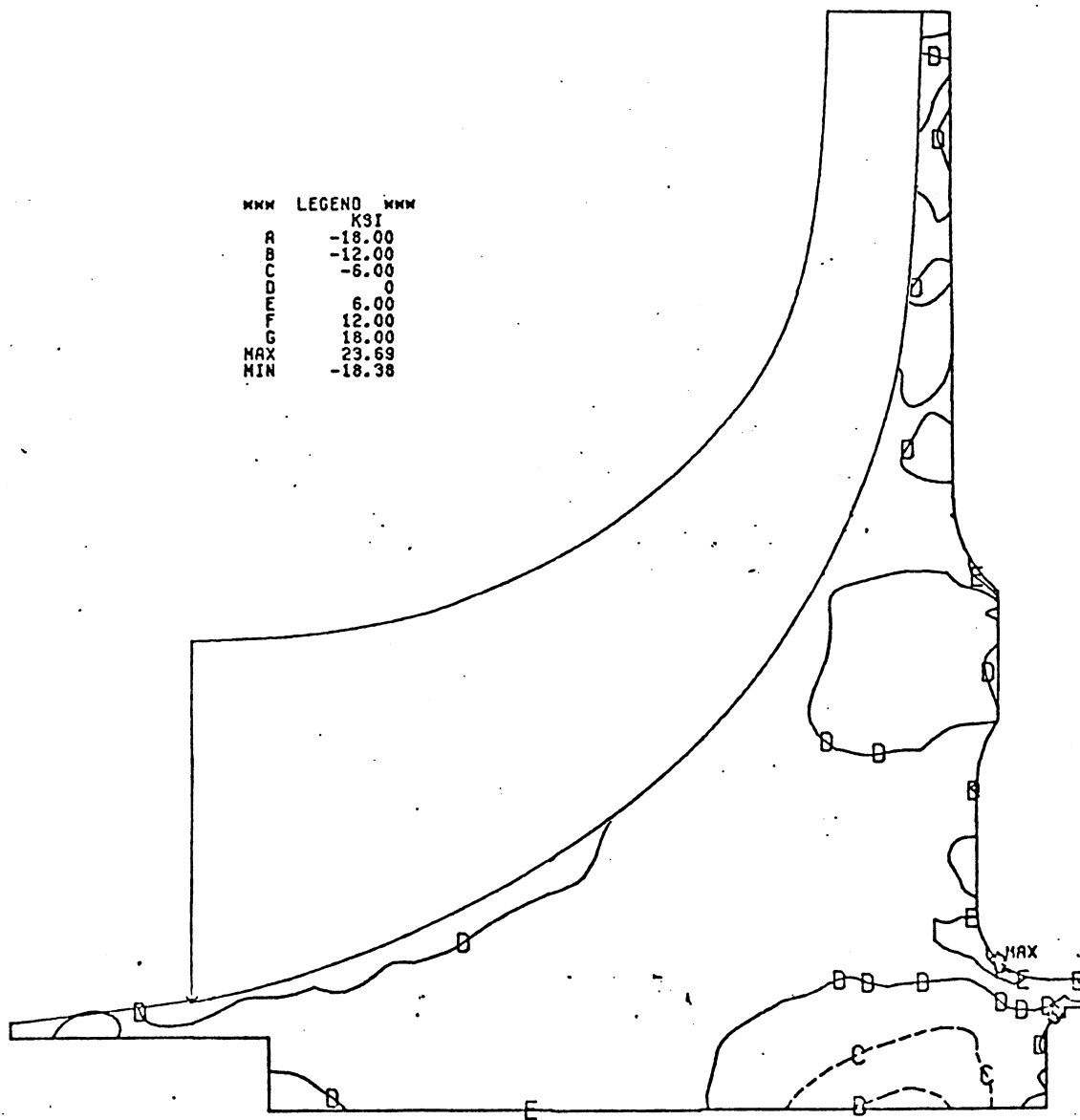


Figure 18. Impeller Axial Stresses.

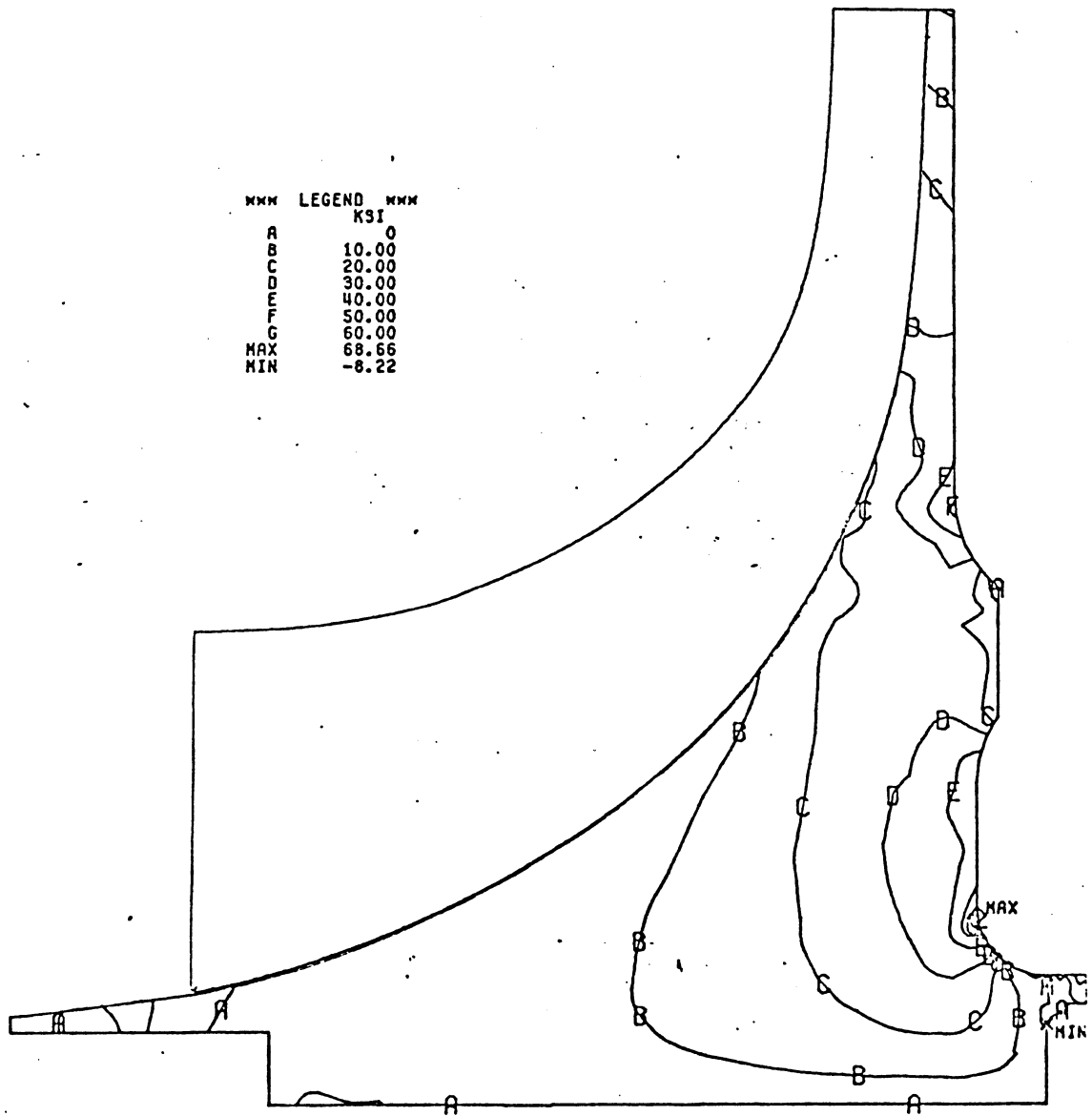


Figure 19. Impeller Radial Stresses.

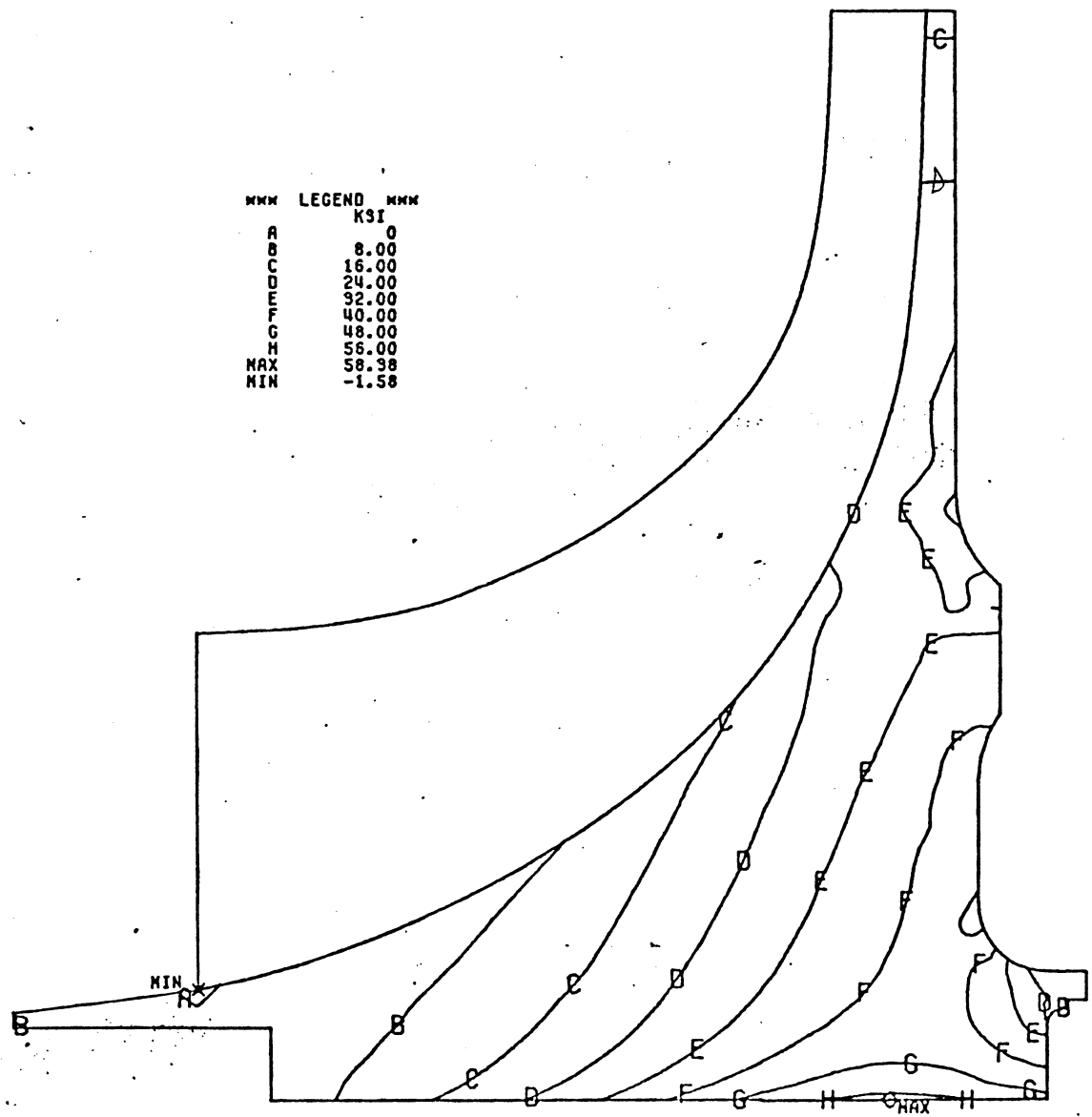


Figure 20. Impeller Tangential Stresses.

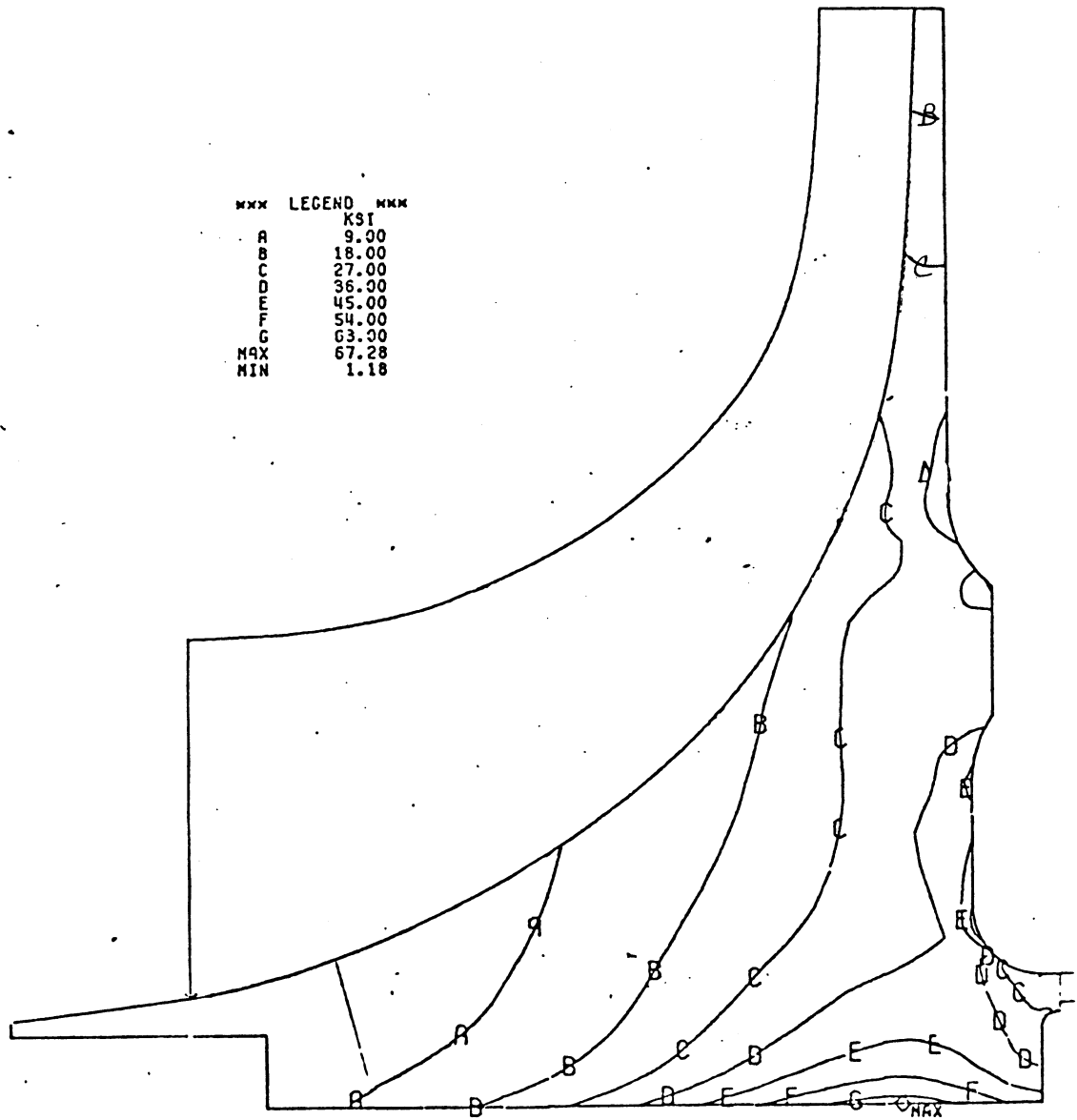
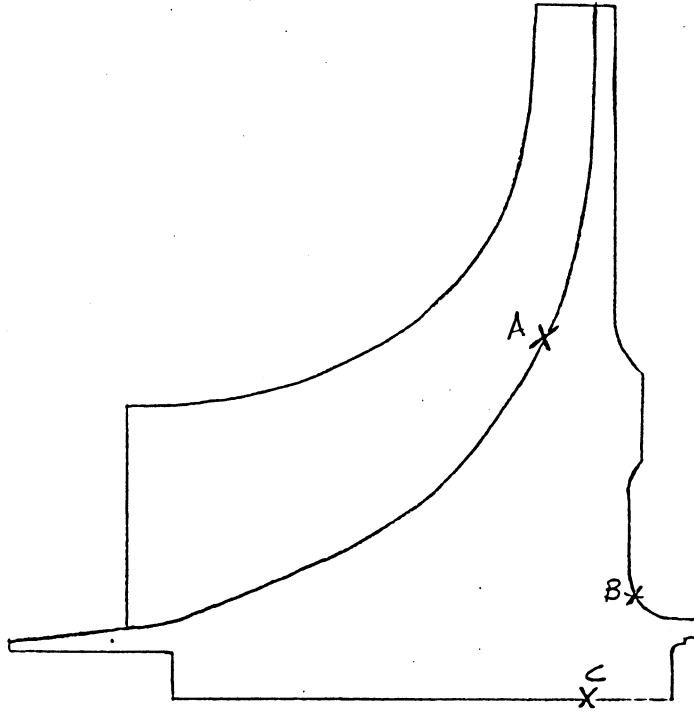


Figure 21. Impeller Equivalent Stress with 10,000 lbf Axial Load.



Location	$\sigma_{MAX}(KSI)$	K_t	R_{RATIO}	Life (cycles)		-3σ Yield Strength (KSI)
				Mean	Temp(°F)	
A *	58.5	1.35	0.0	$> 10^6$	140	106
B	61.66	1.0	0.0	$> 10^6$	116	110
C	67.2	1.0	0.0	$> 10^6$	114	110

* Max. Stress in the Backplate (From Triangular Plate Model)

-3 σ Burst Speed

Avg. Tang. = 199% N_D
 Avg. Radial = 182% N_D

Figure 22. Low Cycle Fatigue and Burst Analysis

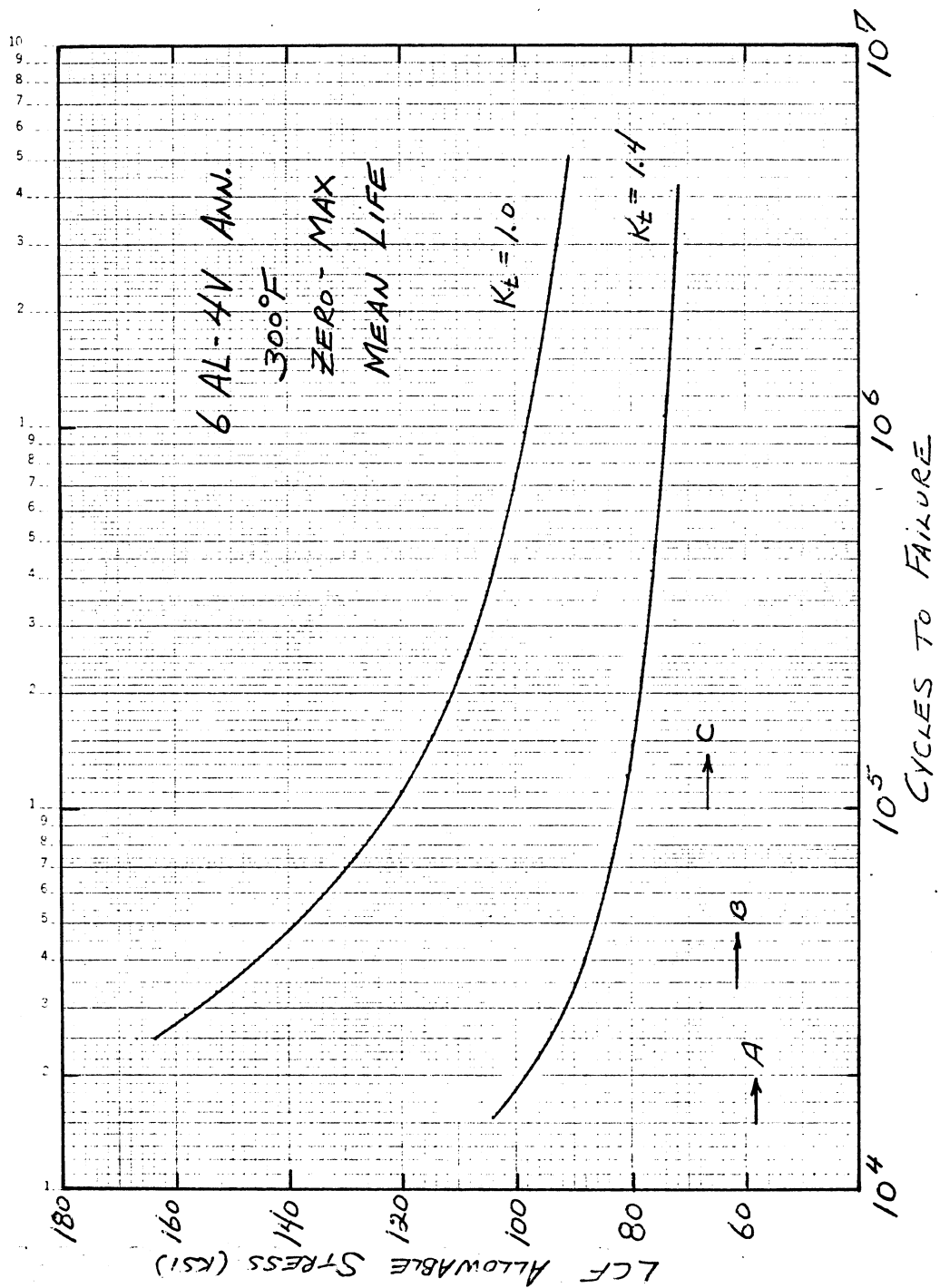


Figure 23. Low Cycle Fatigue Material Properties for Ti 6AL4V.

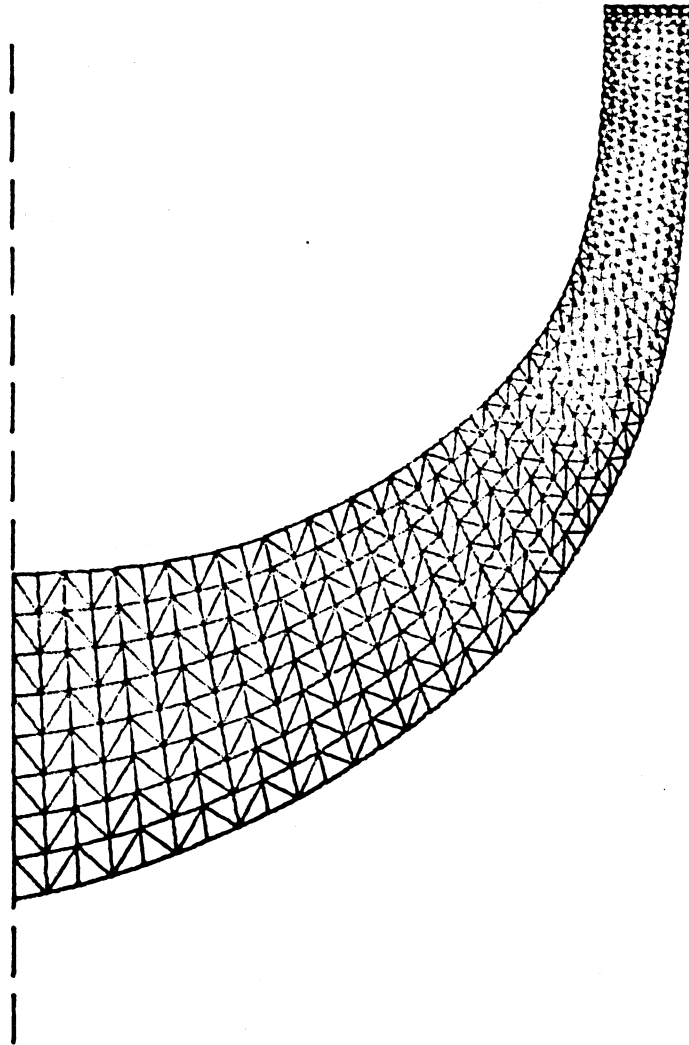


Figure 24. Triangular Plate Model for Scaled Impeller Full Blade.

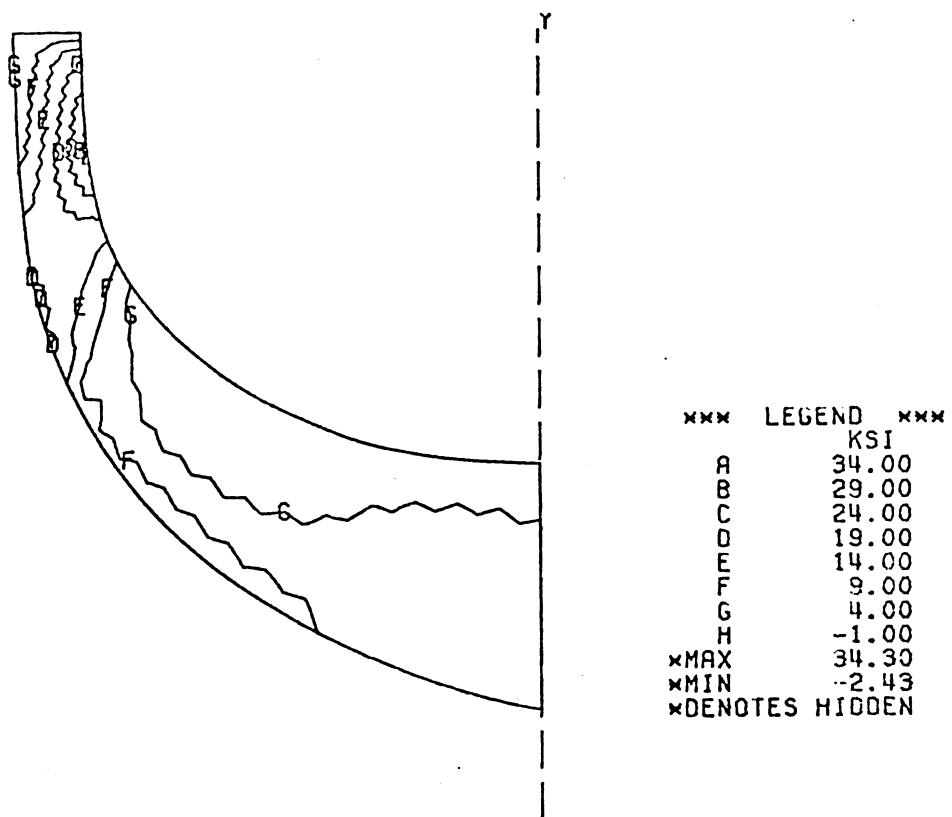


Figure 25. Pressure Surface ~ Maximum Principal Stress.

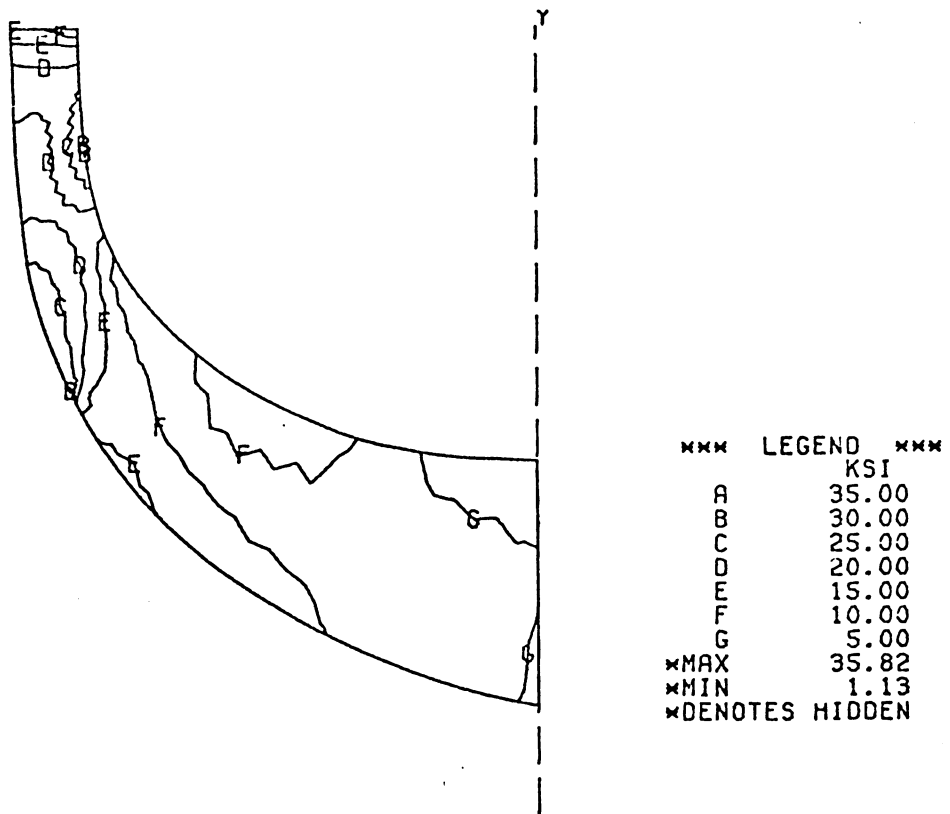


Figure 26. Pressure Surface ~ Equivalent Stress.

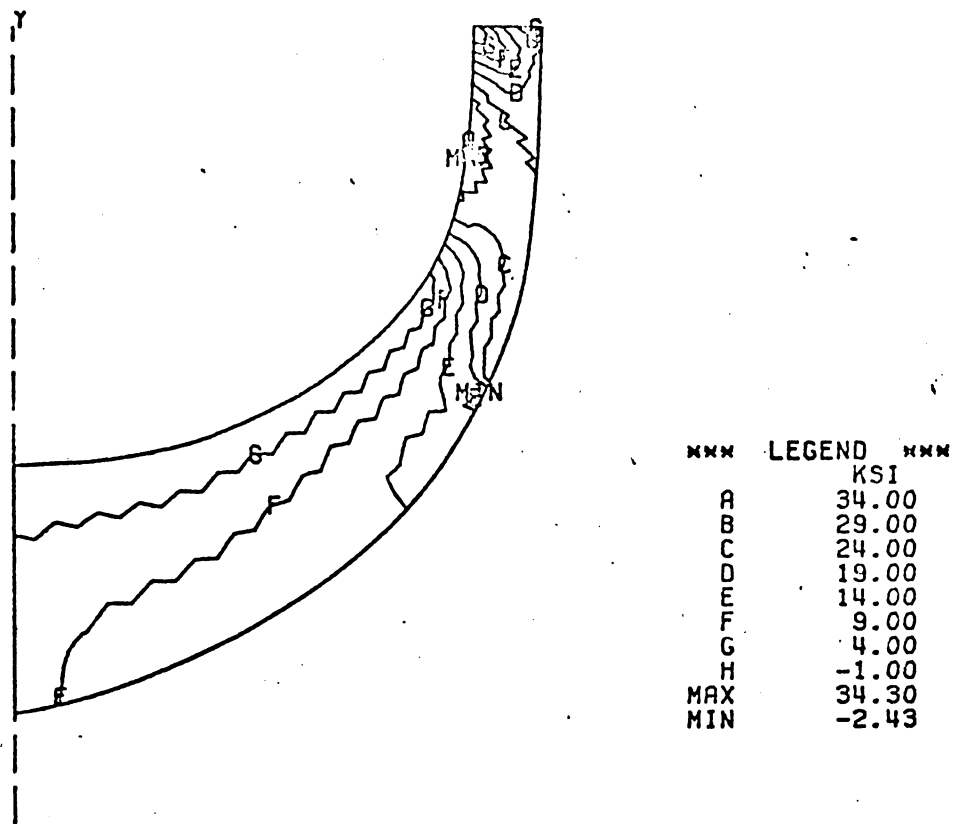


Figure 27. Suction Surface ~ Maximum Principal Stress.

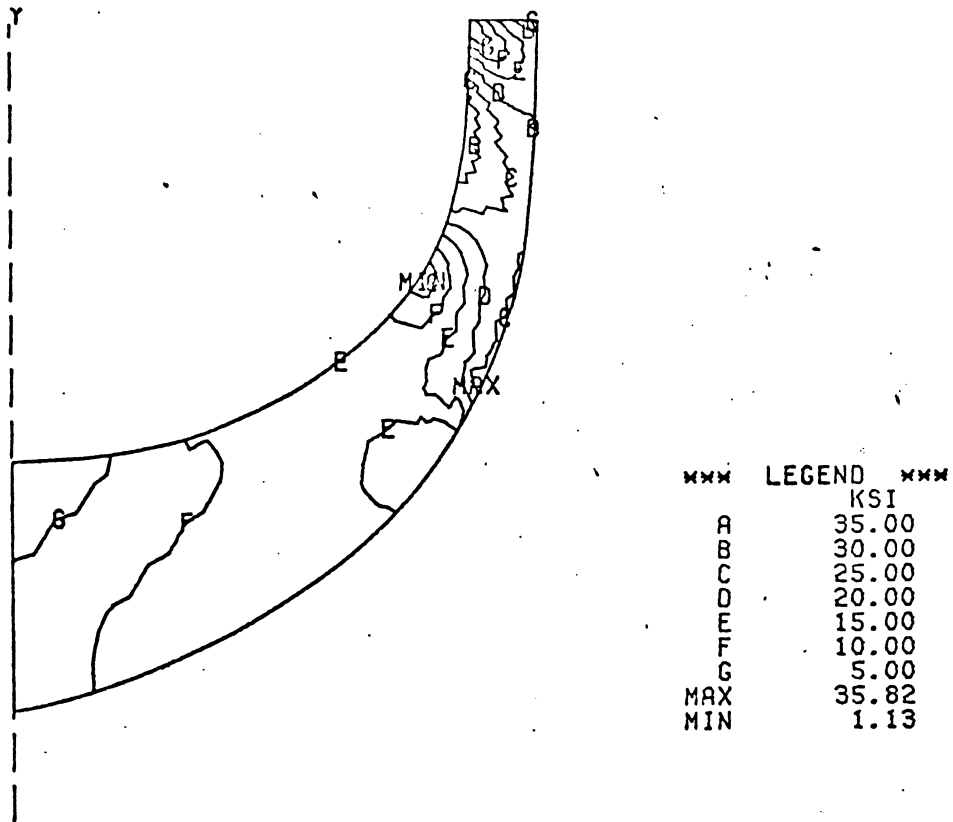


Figure 28. Suction Surface ~ Equivalent Stress.

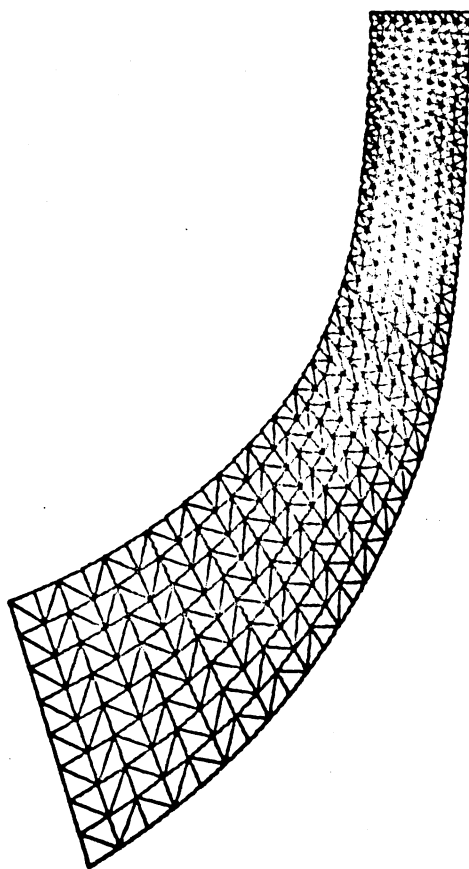


Figure 29. Triangular Plate Model for Scaled Impeller Splitter Blade.

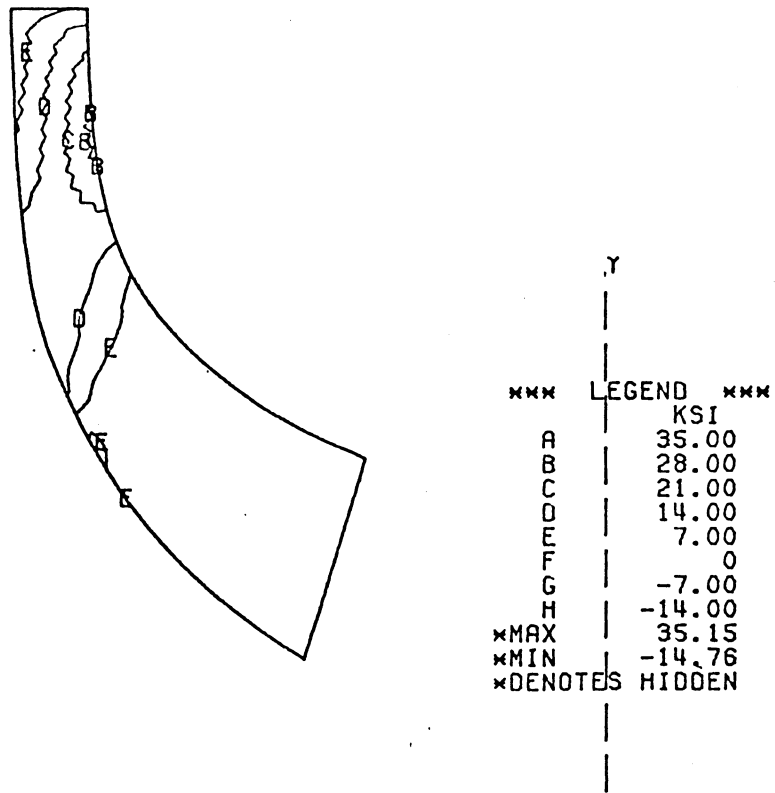


Figure 30. Pressure Surface ~Maximum Principal Stress.

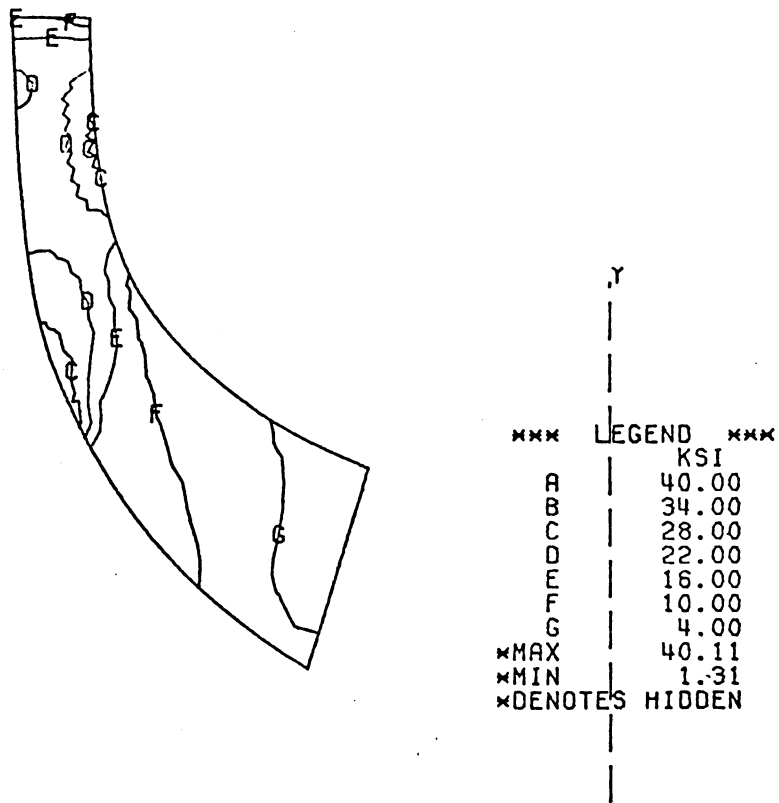


Figure 31. Pressure Surface ~ Equivalent Stress.

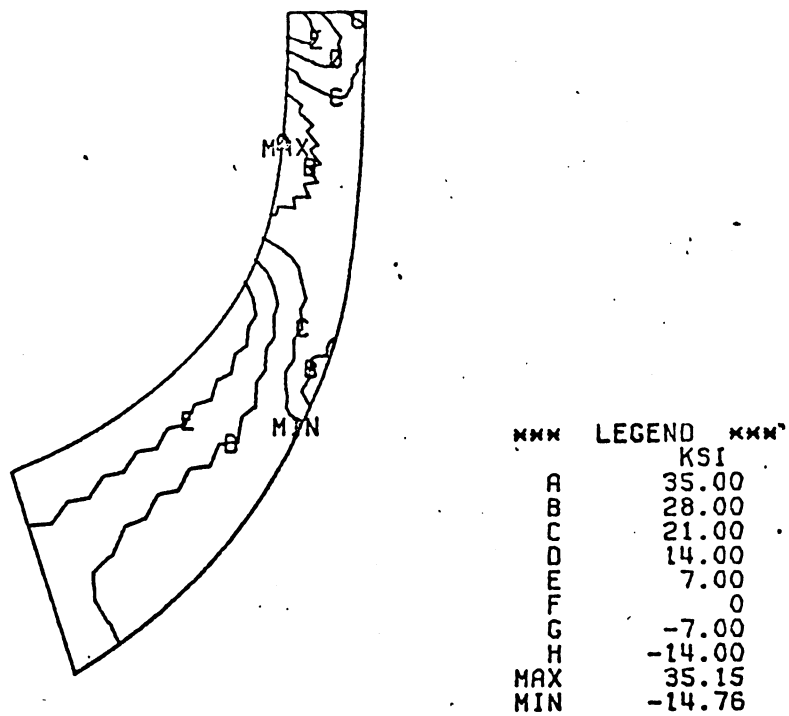


Figure 32. Suction Surface ~ Maximum Principal Stress.

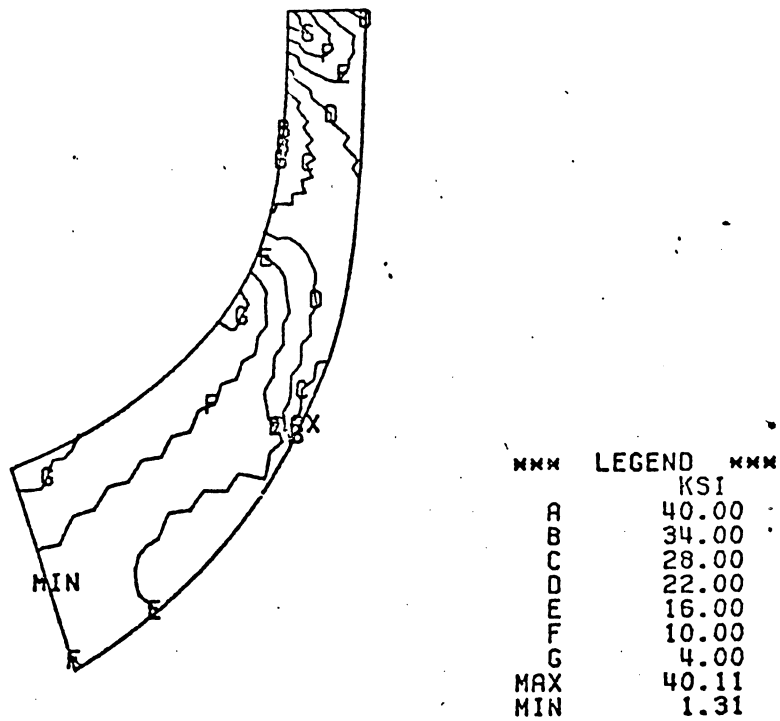


Figure 33. Suction Surface ~ Equivalent Stress.

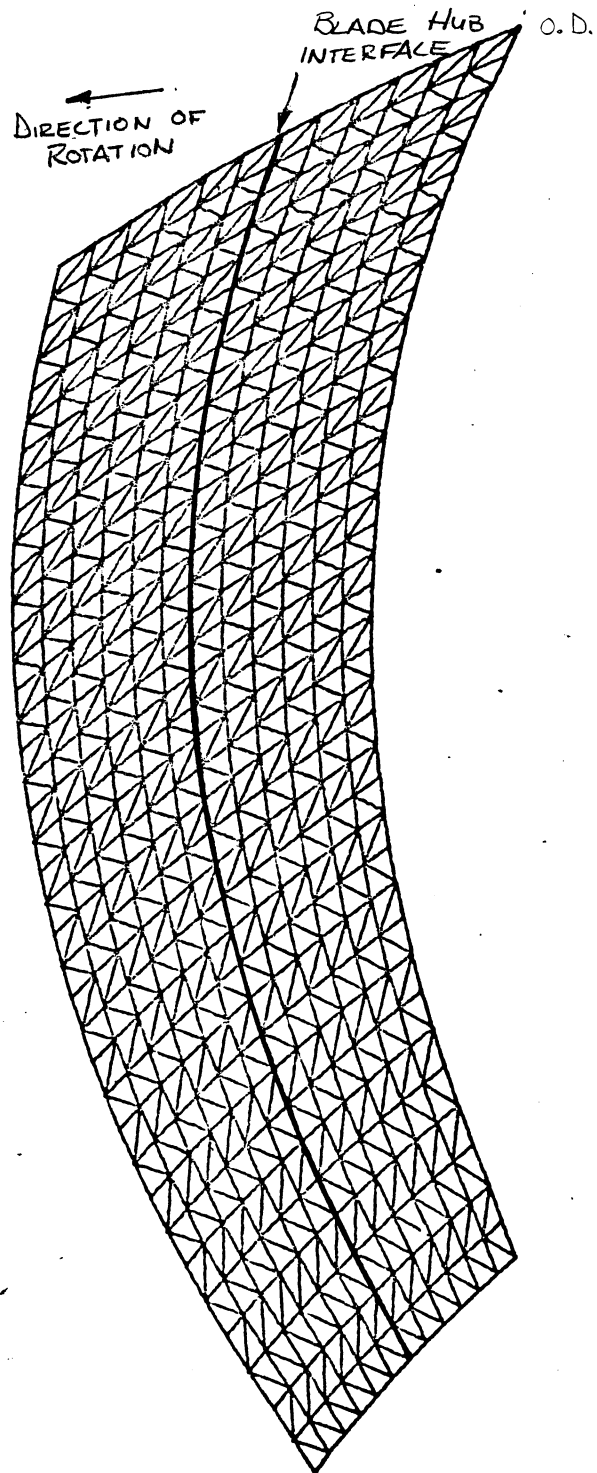


Figure 34. Triangular Plate Model for Impeller Backplate.

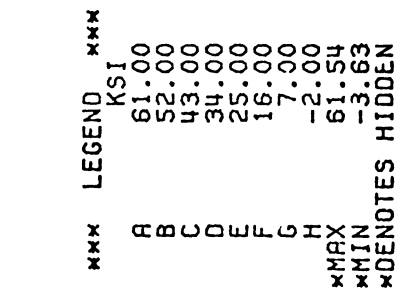


Figure 35. Maximum Principal Stress ~ Backface Surface.

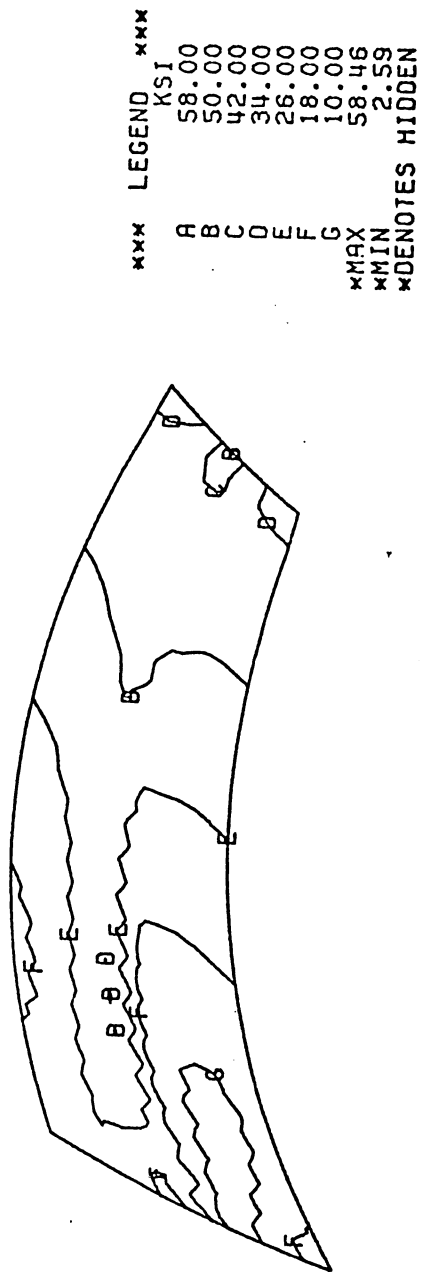


Figure 36. Equivalent Stress ~ Backface Surface.

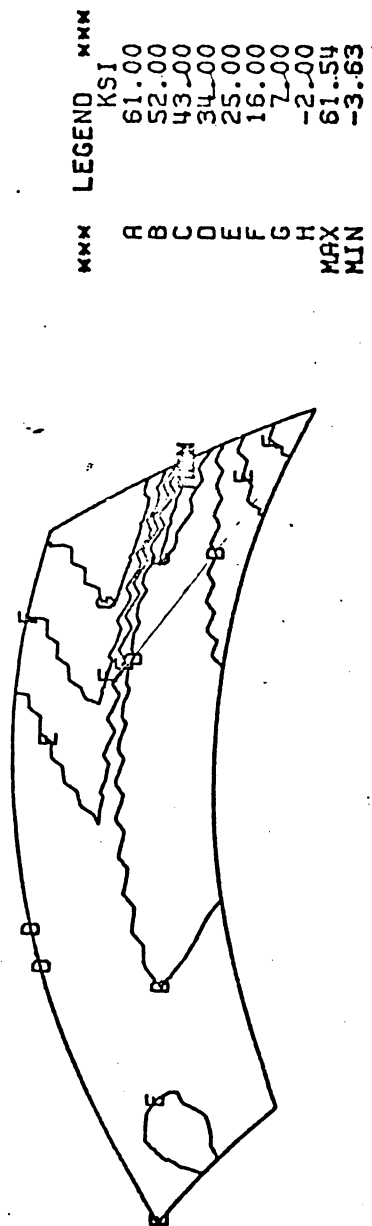


Figure 37. Maximum Principal Stress ~ Flowpath Hub Surface.

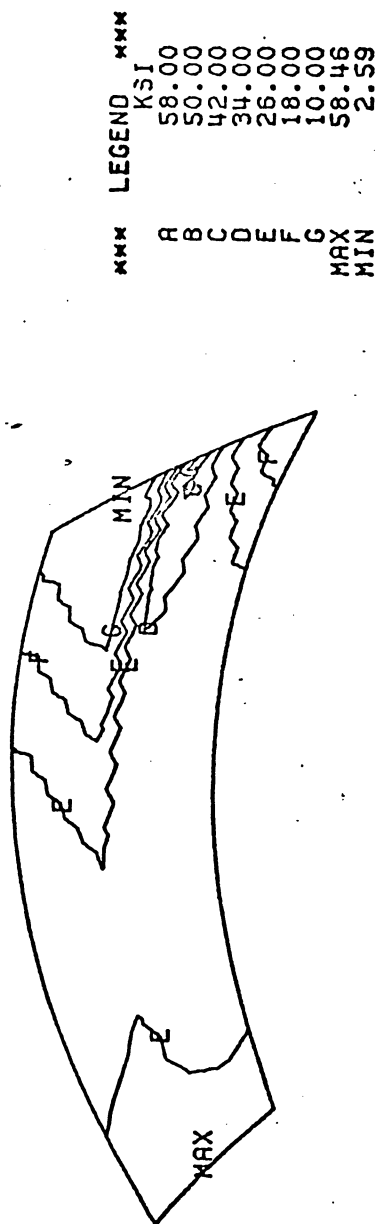


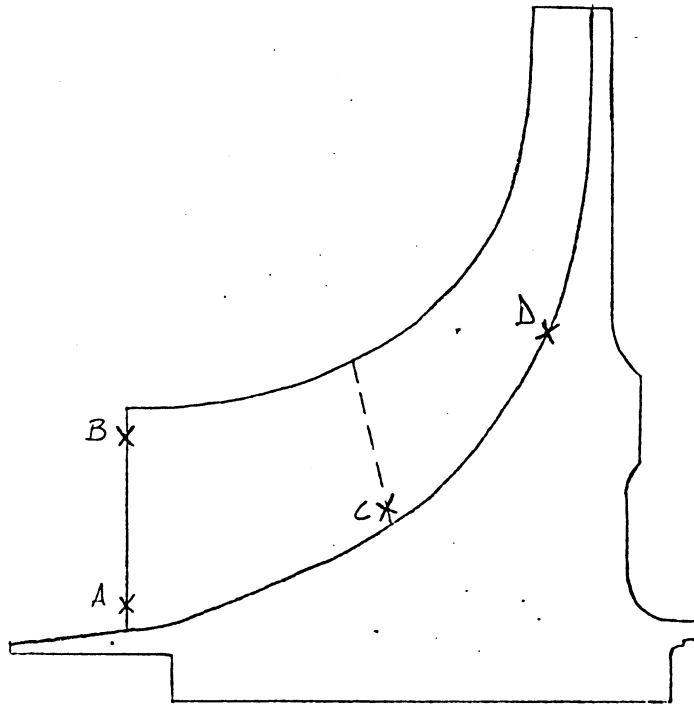
Figure 38. Equivalent Stress ~ Flowpath Hub Surface.

Maximum equivalent stresses from the triangular plate analysis are summarized in Figure 39. Locations A and B are on the full blade leading edge, C is on the splitter leading edge and D is at the maximum stress location on both the full blade and splitters. Based on the stresses and stress concentration factors defined in Figure 39 and the Goodman diagram presented in Figure 40, a high cycle fatigue analysis was performed. The maximum steady stress location on the splitter yielded the lowest vibratory allowable stress, 14.4 ksi.

The final output of the static stress analysis was a complete definition of the deflection characteristics of the wheel, backplate and blade geometry. This definition was used to convert the "hot running" aerodynamic geometry into an equivalent manufacturing, "cold", definition. Details of this conversion and the resulting manufacturing definition are presented in Section IV.

A summary of pertinent deflections is given in Figure 41. Of special interest are points 5 and 2. The calculated axial deflection at the impeller exit was 0.01463 inches with ground located near the impeller leading edge. This axial deflection must be accounted for in the establishment of cold build clearance. Point 2 is at the location of the curvic coupling. With point 1 grounded, the change in axial wheel length between points 1 and 2 is 0.00337 inches with the wheel length shortening due to Poisson's effect. This shortening must be accounted for by initial tie bolt stretch.

Finite element models similar to those used for static stress analysis were prepared for vibrational analysis. Resulting frequencies and mode shapes for the first 8 natural frequencies for the full blade and first 3 for the splitter are presented in Figures 42 through 52. A summary of these predicted frequencies is shown on a frequency-speed diagram for the full blade in Figure 53 and for the splitter in Figure 54. The first mode of the full blade is well above 4th harmonic of rotor speed and is, therefore, not susceptible to inlet distortion induced excitation that is often characterized by strong 2nd order



Location	K_t	Mean Stress (KSI)	-3σ Allow. Vib. (KSI)
A	3.0	7.4	15.7
B	3.0	4.8	16.1
C **	3.0	12.4	15.0
D *	1.35	35.8	15.1
D ***	1.35	40.11	14.4

- * Blade Max. Stress
- ** Splitter Leading Edge
- *** Splitter Max. Stress

Figure 39. Summary of High Cycle Fatigue Analysis.

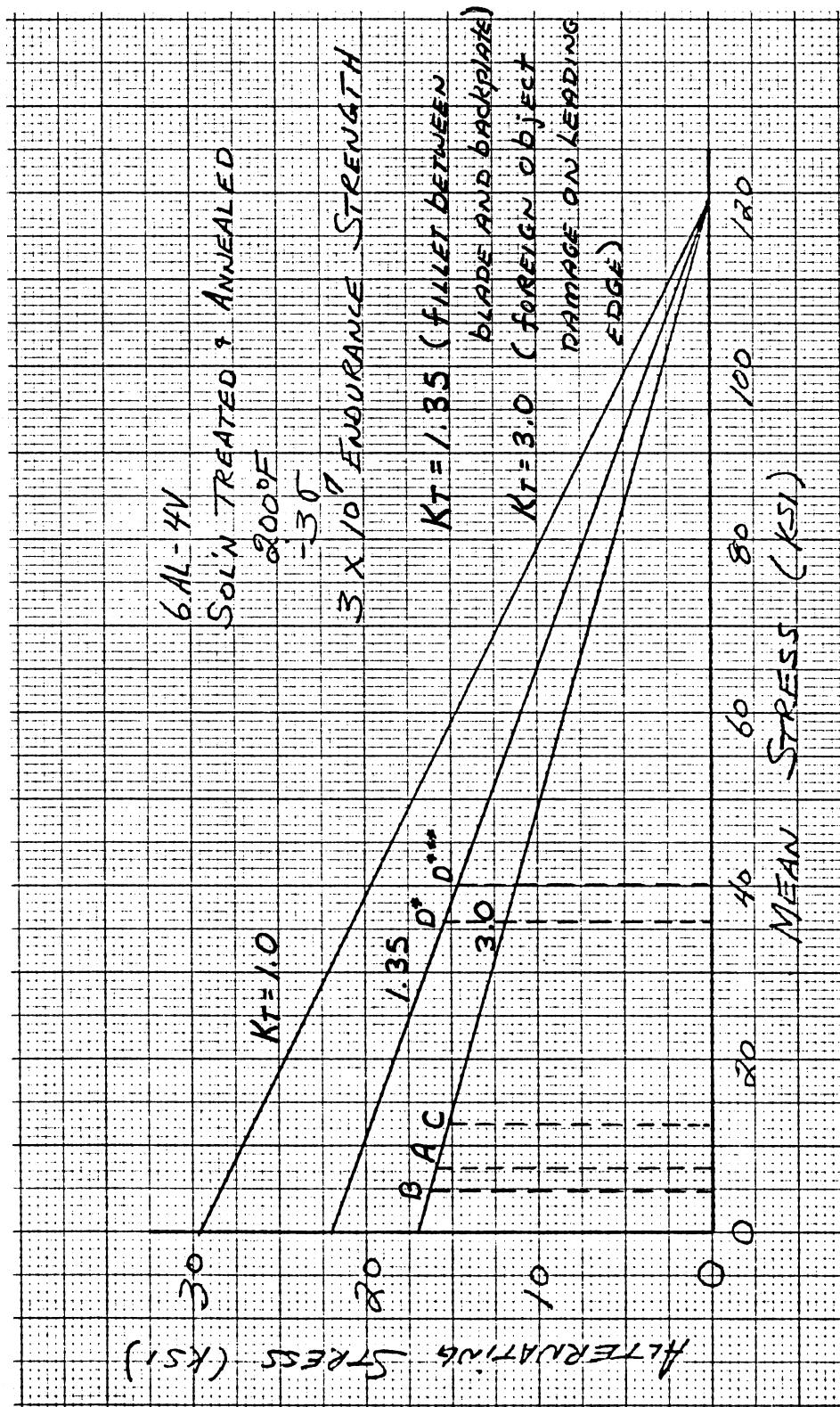


Figure 40. Goodman Diagram for Ti 6AL-4V Material.

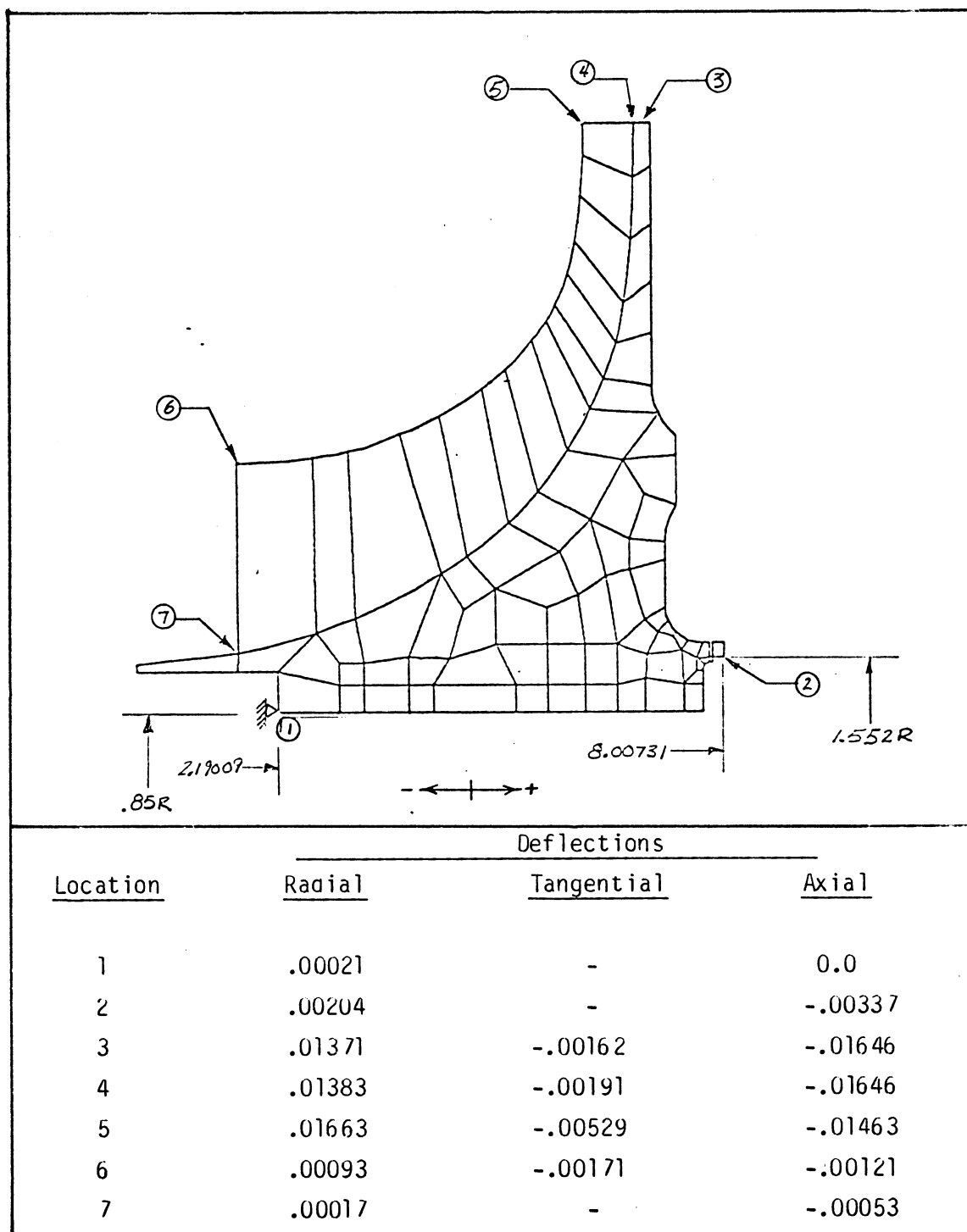


Figure 41. Scaled Impeller Deflection Summary.

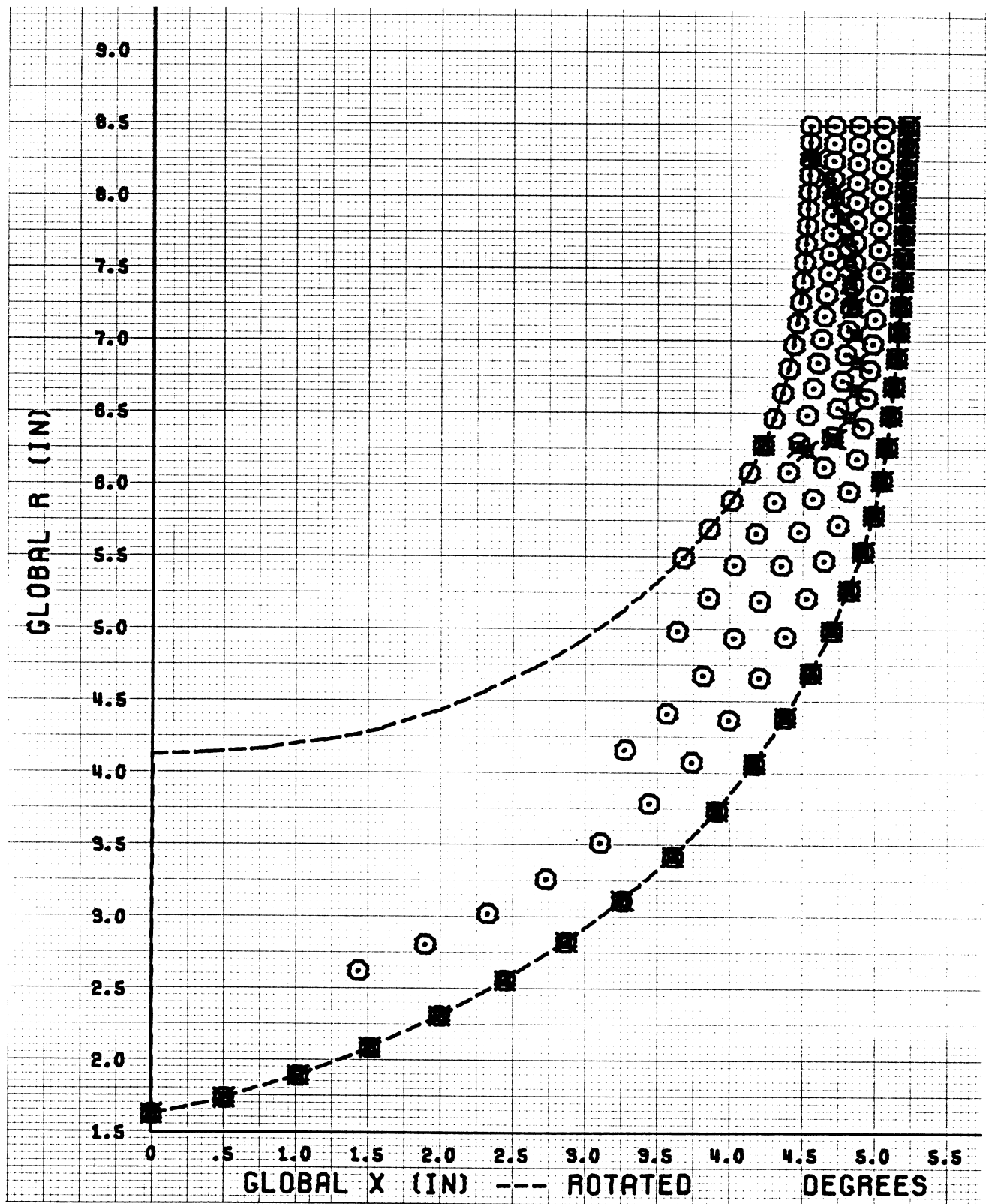
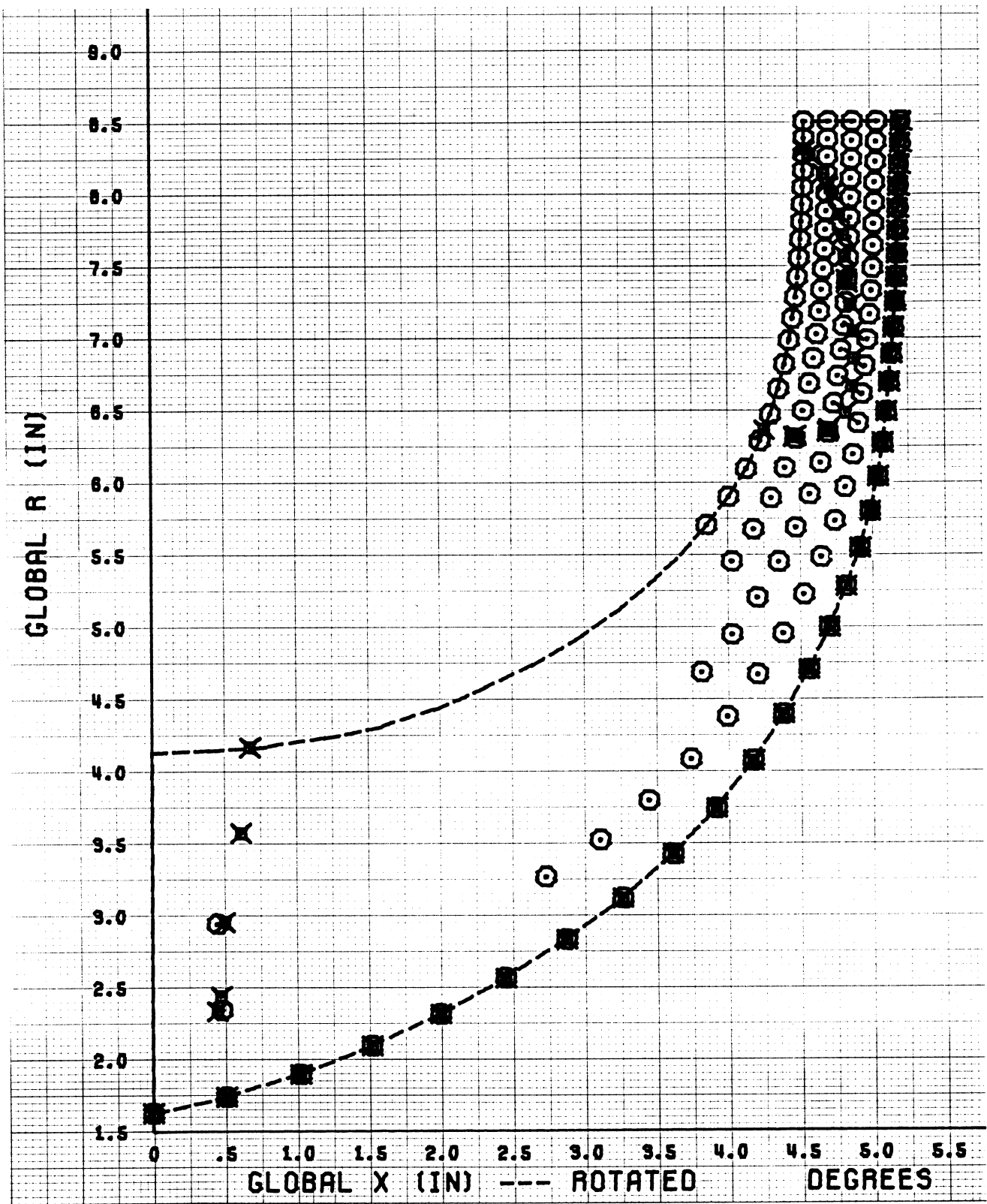


Figure 42. Full Blade ~ 1st Natural Frequency.



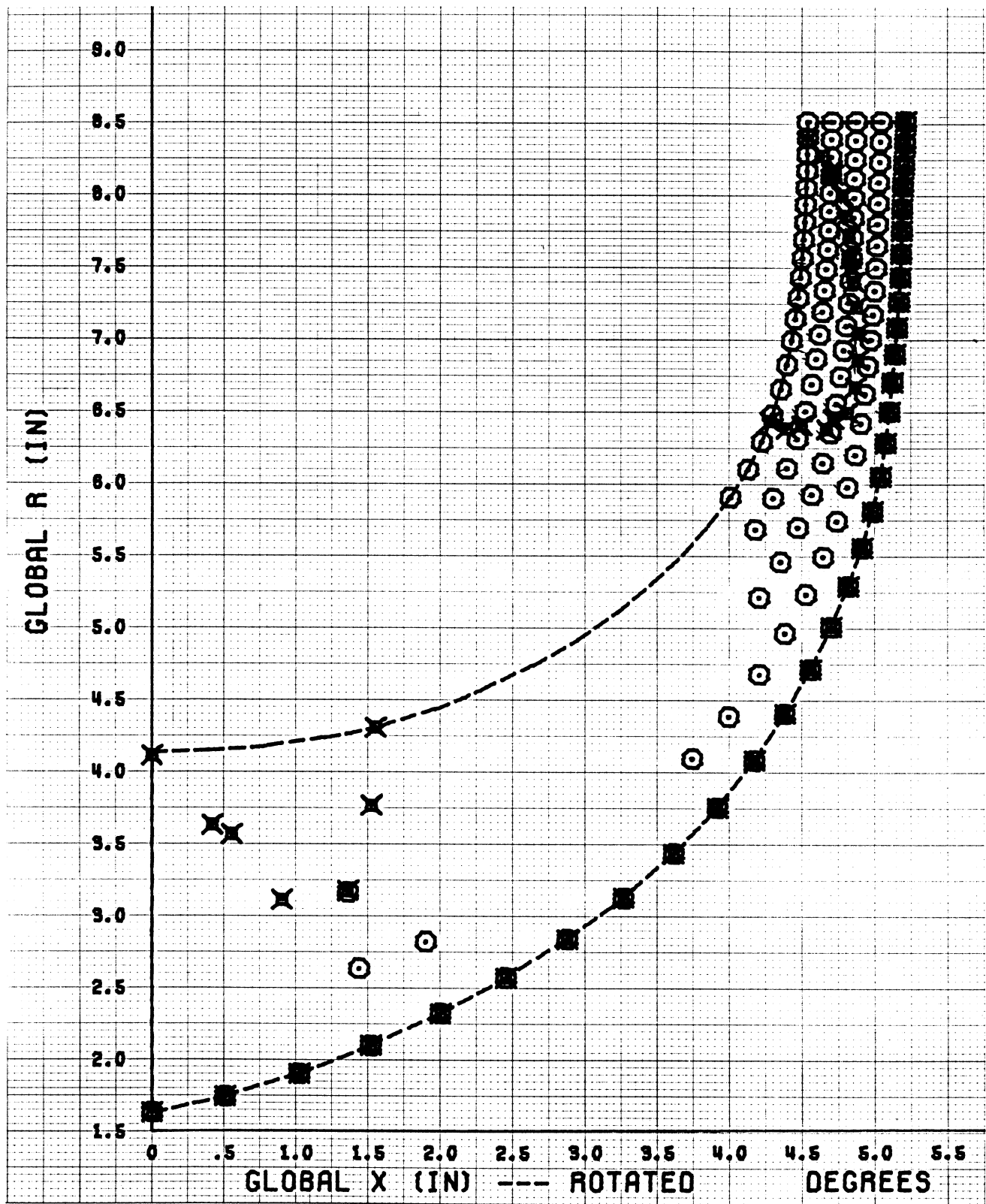


Figure 44. Full Blade ~ 3rd Natural Frequency.

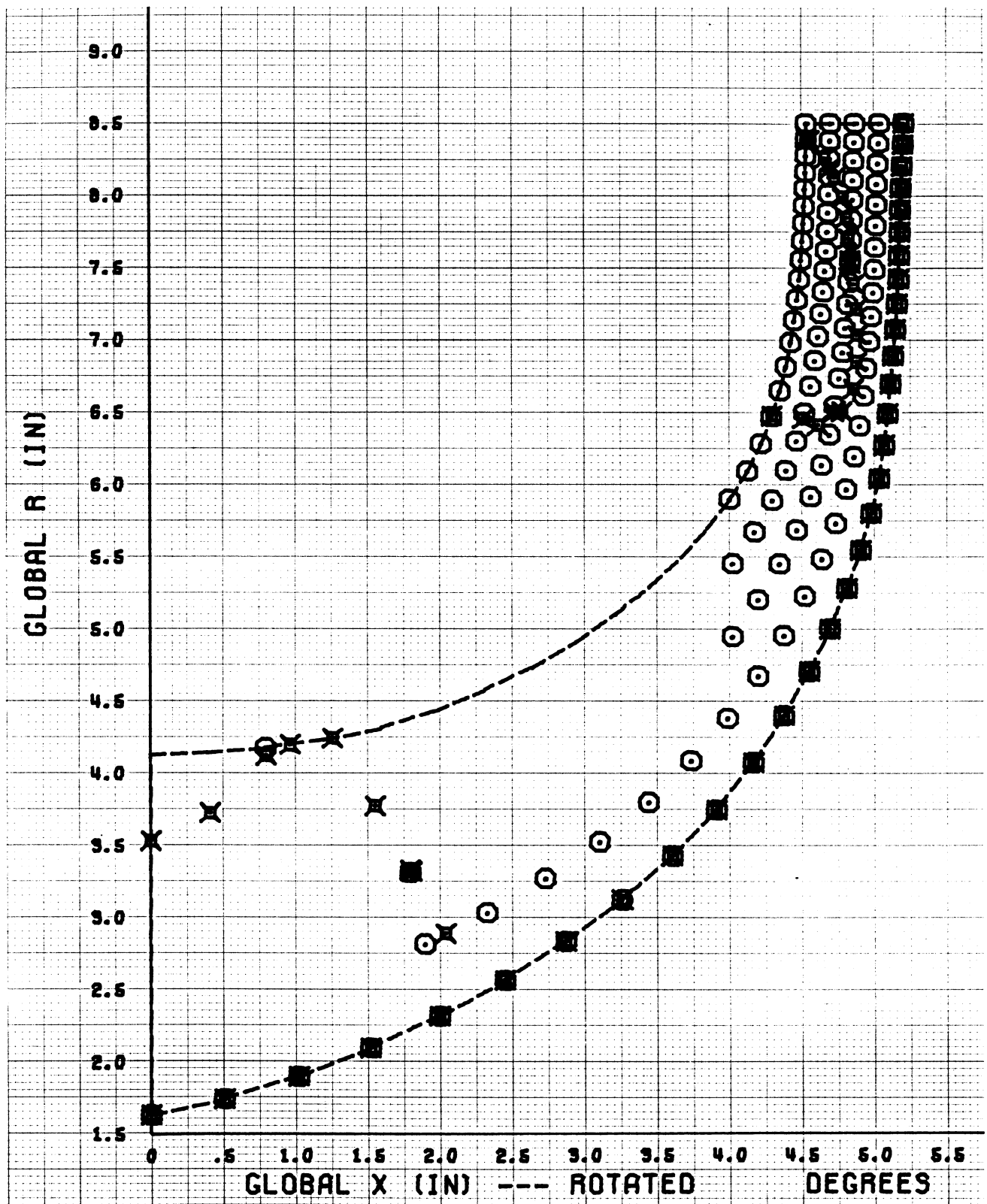


Figure 45. Full Blade ~ 4th Natural Frequency.

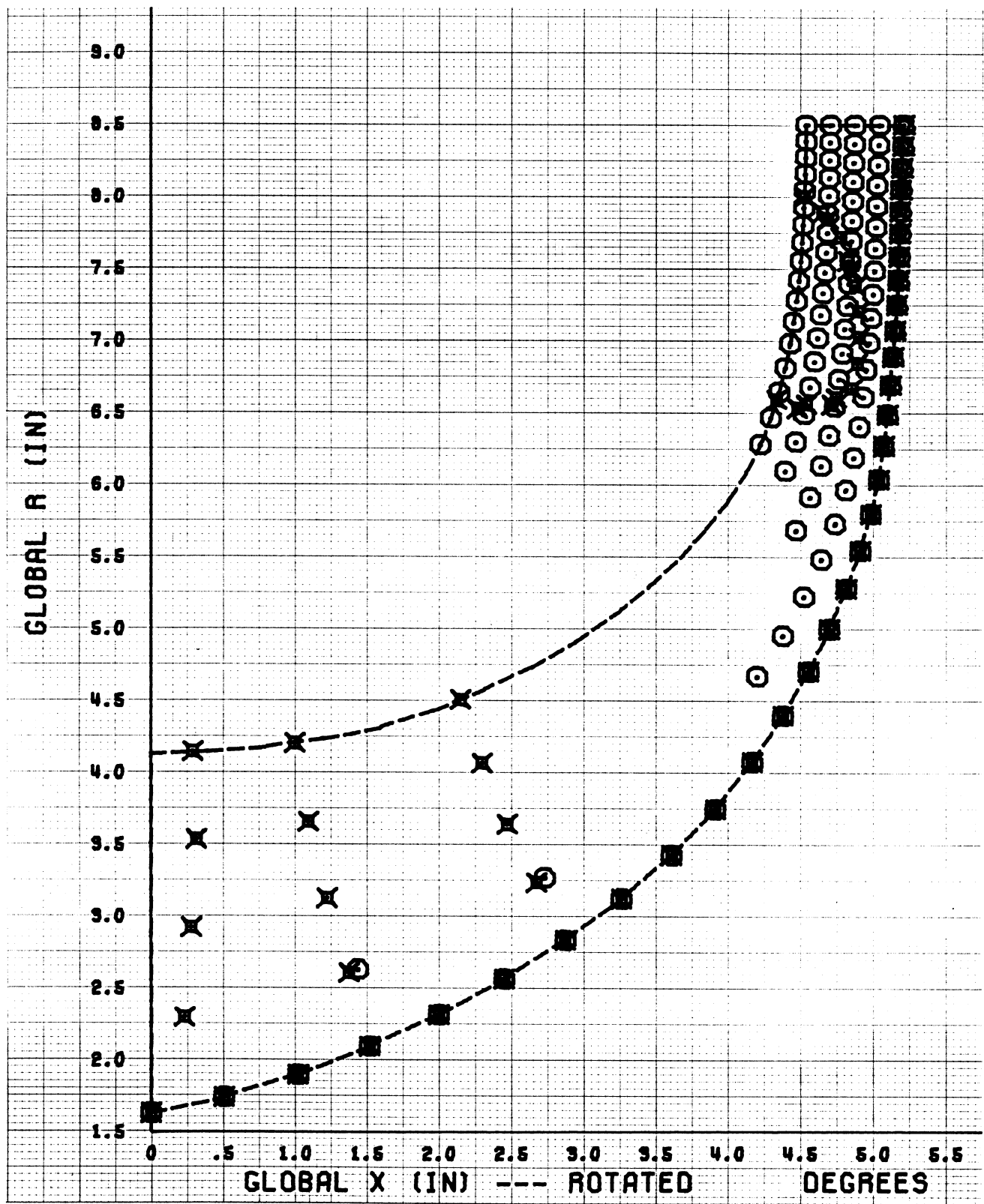


Figure 46. Full Blade ~ 5th Natural Frequency.

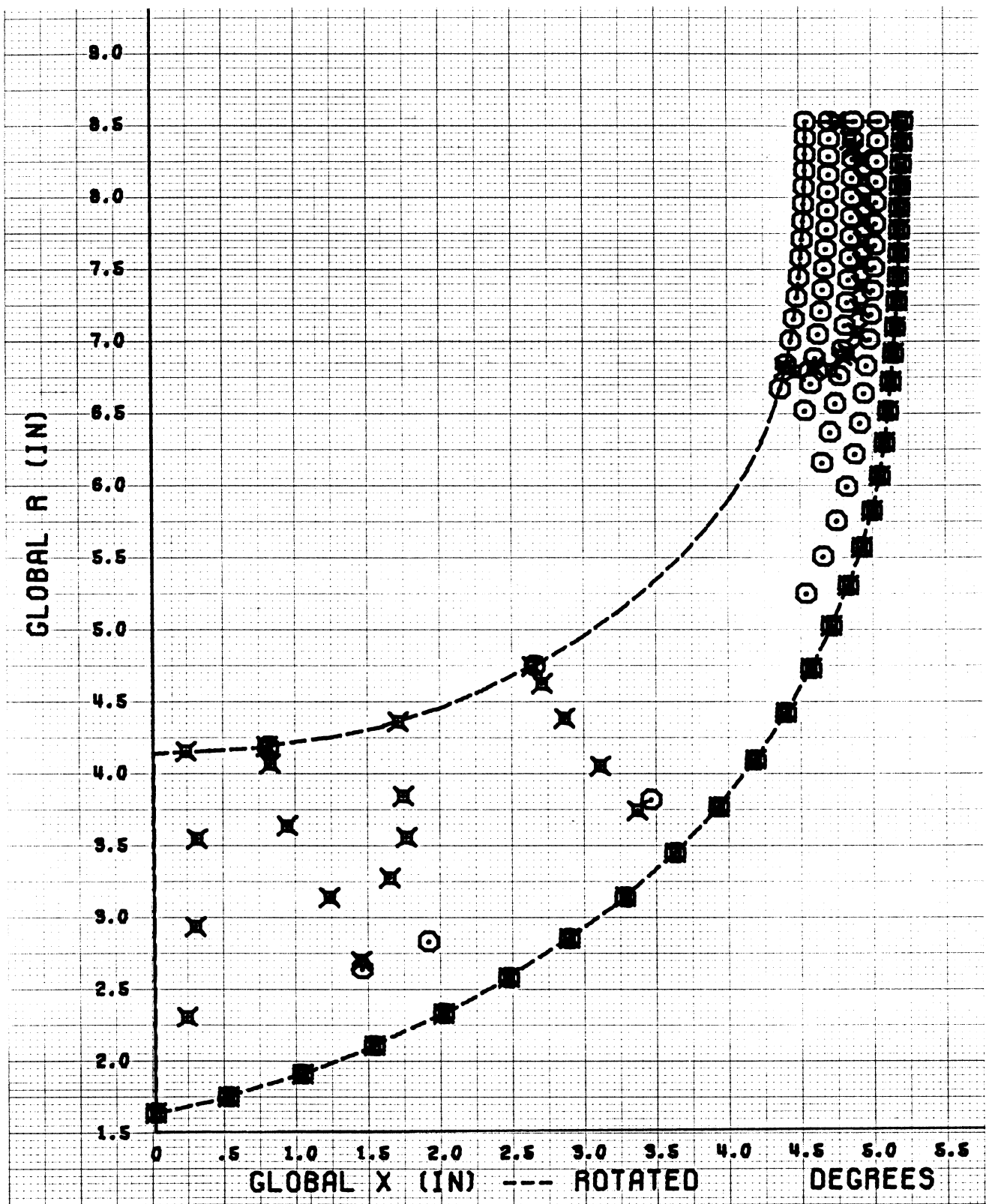


Figure 47. Full Blade ~6th Natural Frequency.

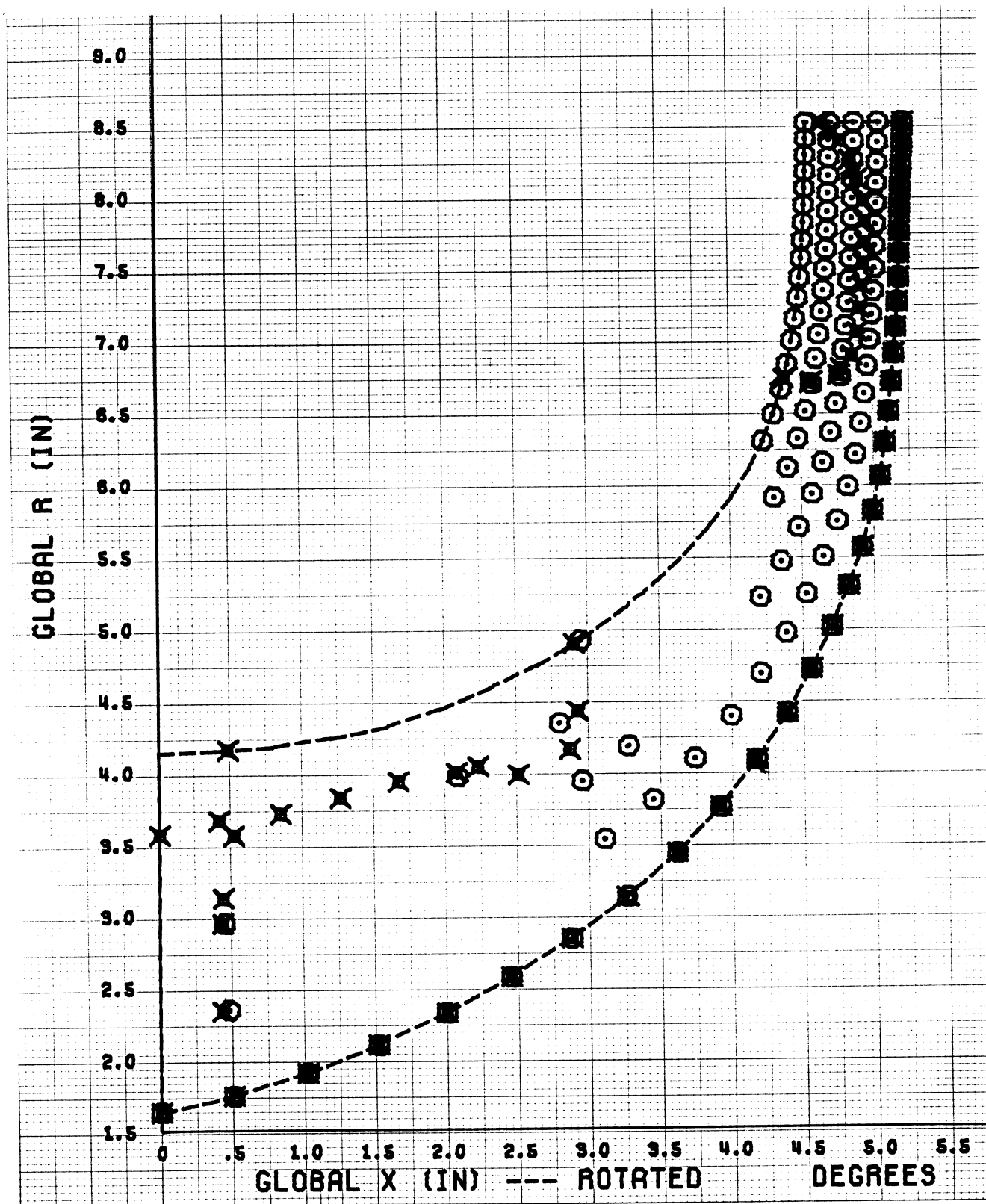
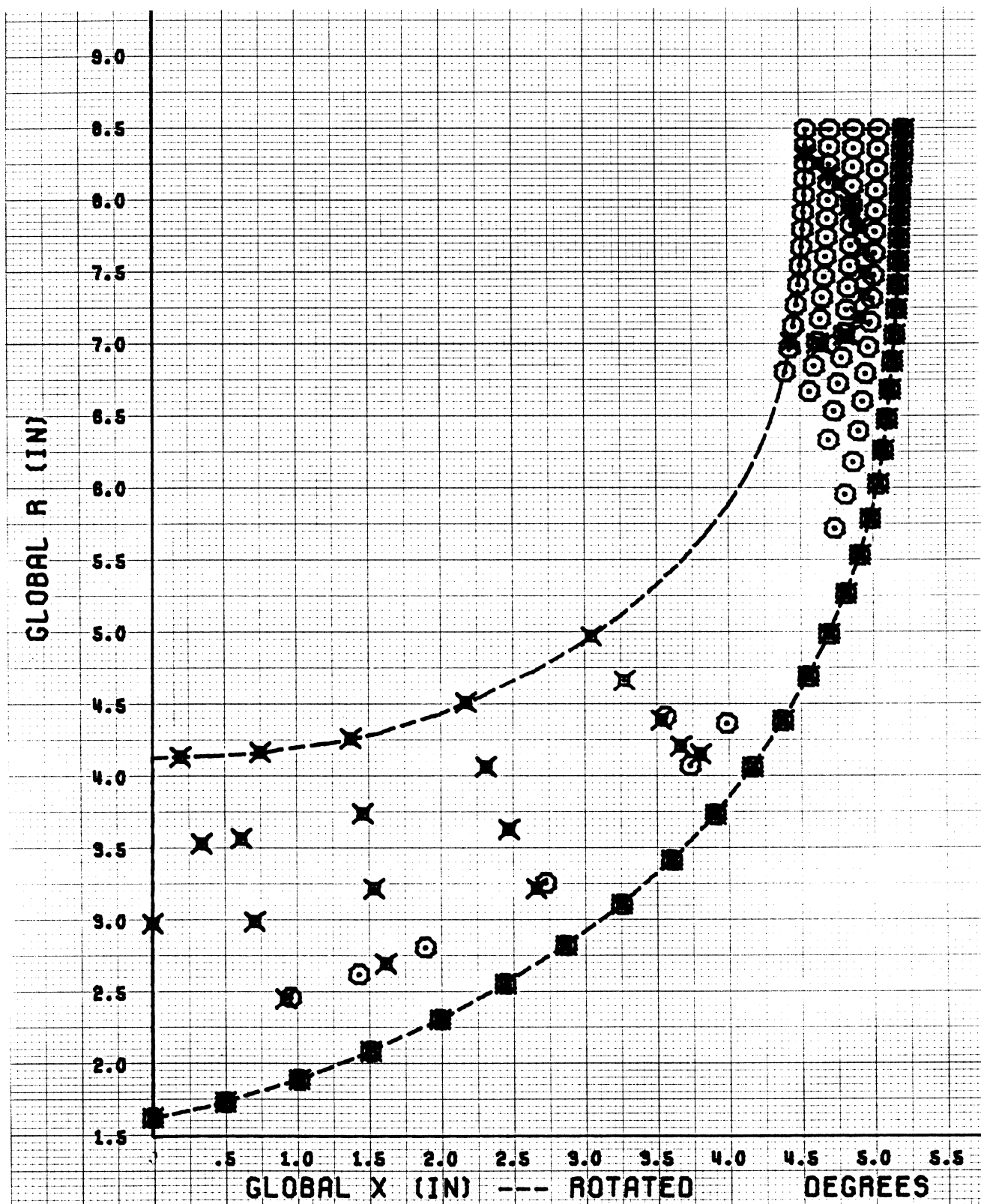


Figure 48. Full Blade ~7th Natural Frequency.



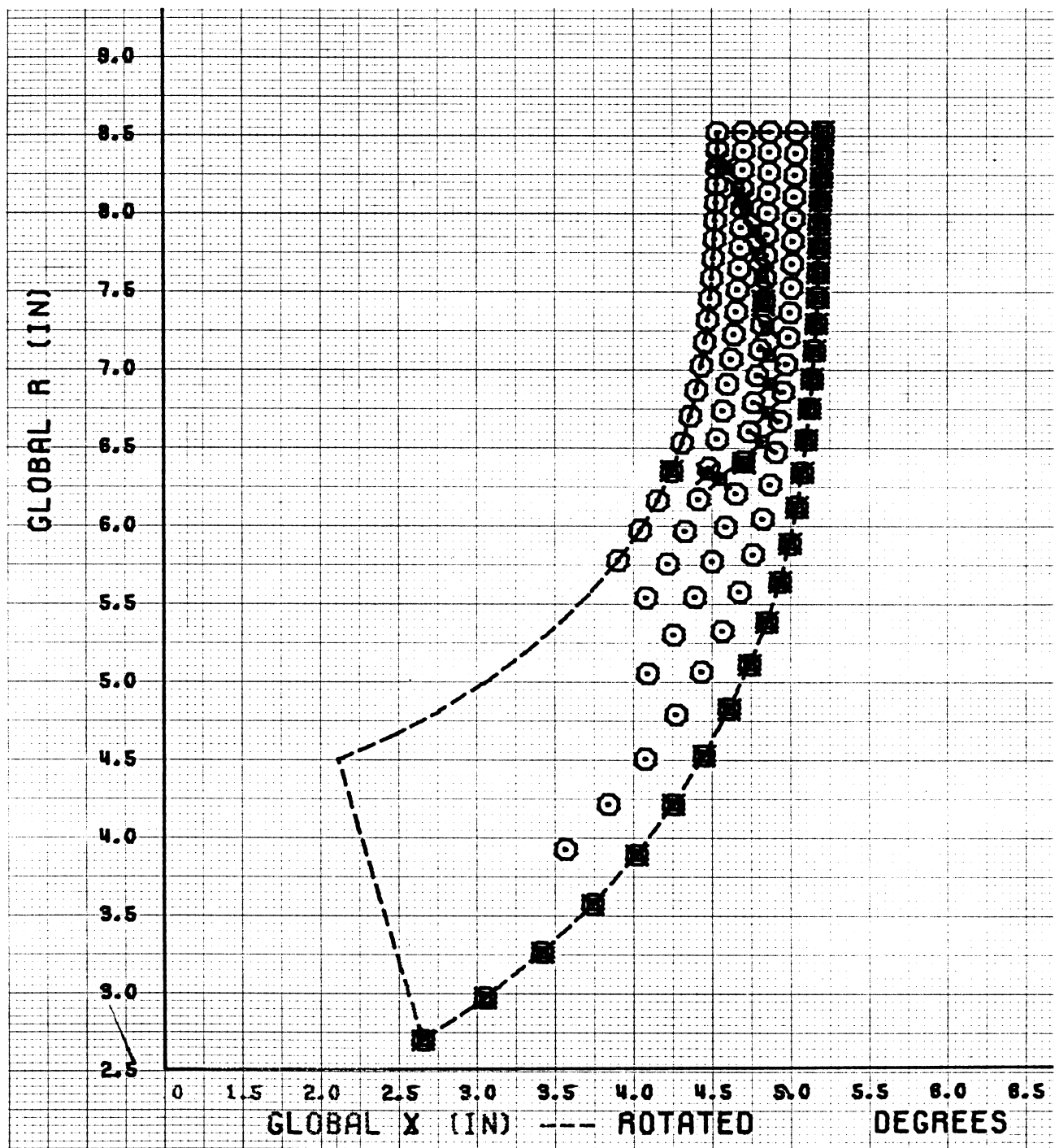


Figure 50. Splitter Blade ~1st Natural Frequency.

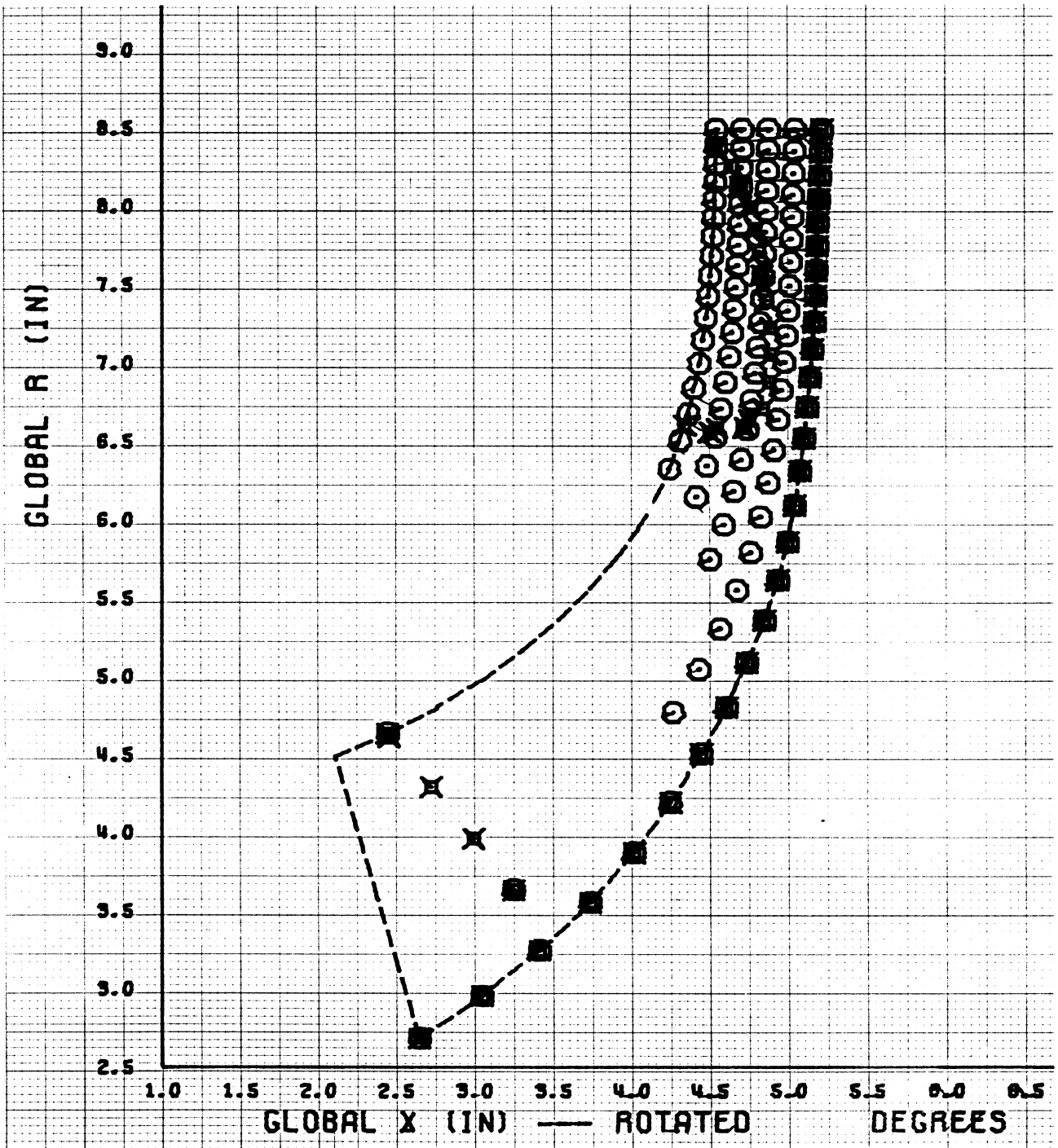


Figure 51. Splitter Blade ~ 2nd Natural Frequency.

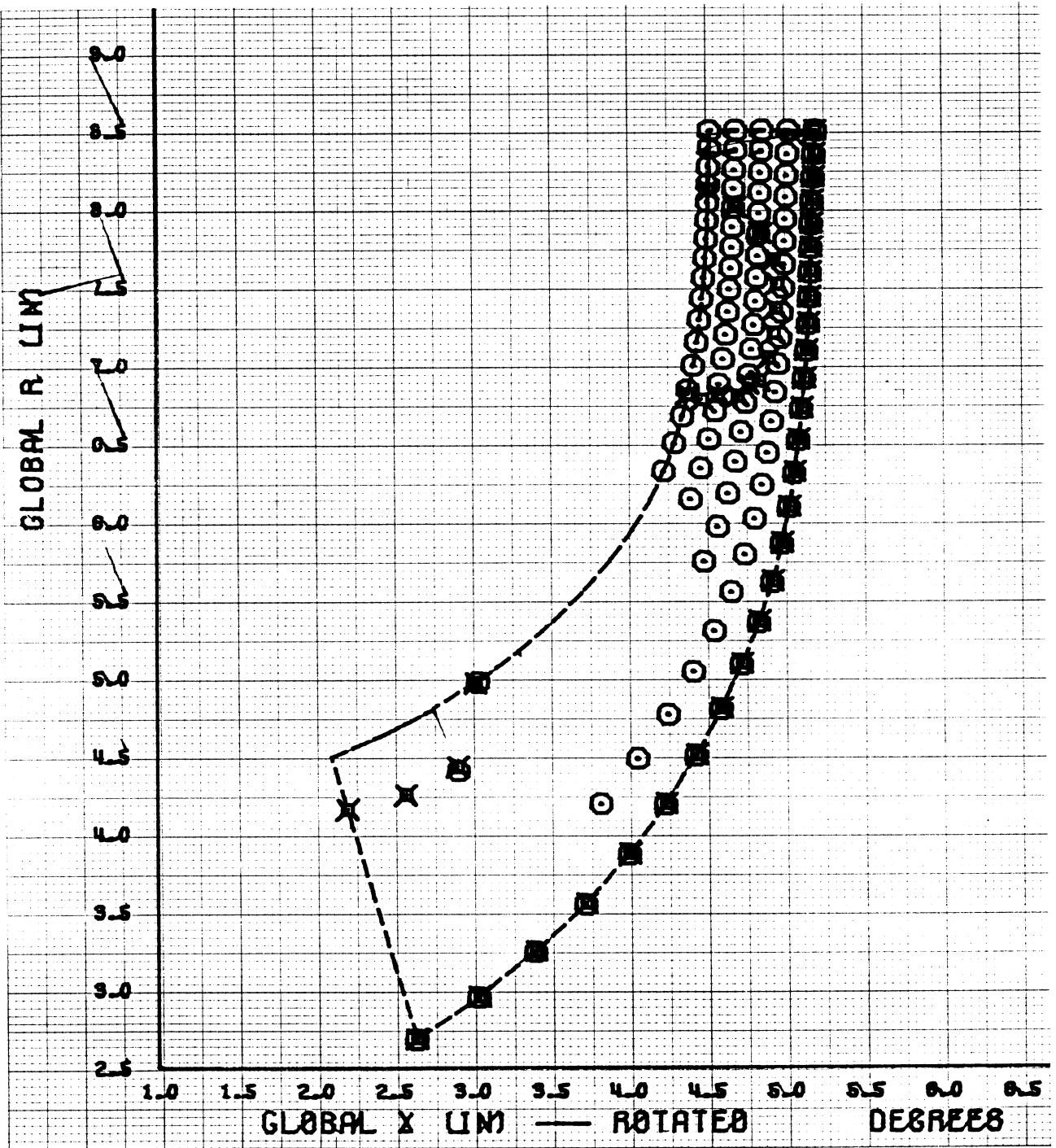


Figure 52. Splitter Blade ~ 3rd Natural Frequency.

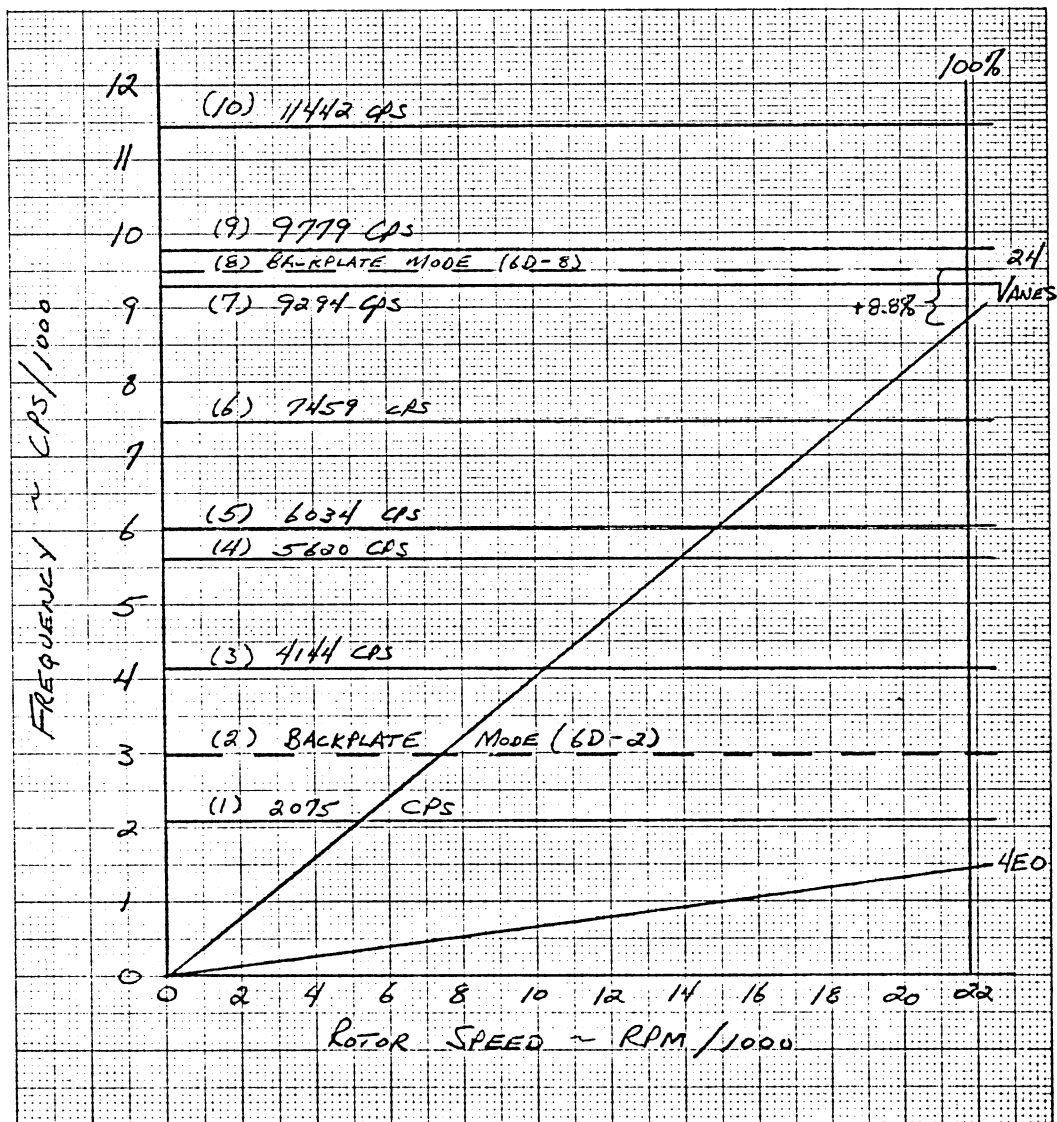


Figure 53. Frequency-Speed Diagram for Full Blade of Scaled Impeller.

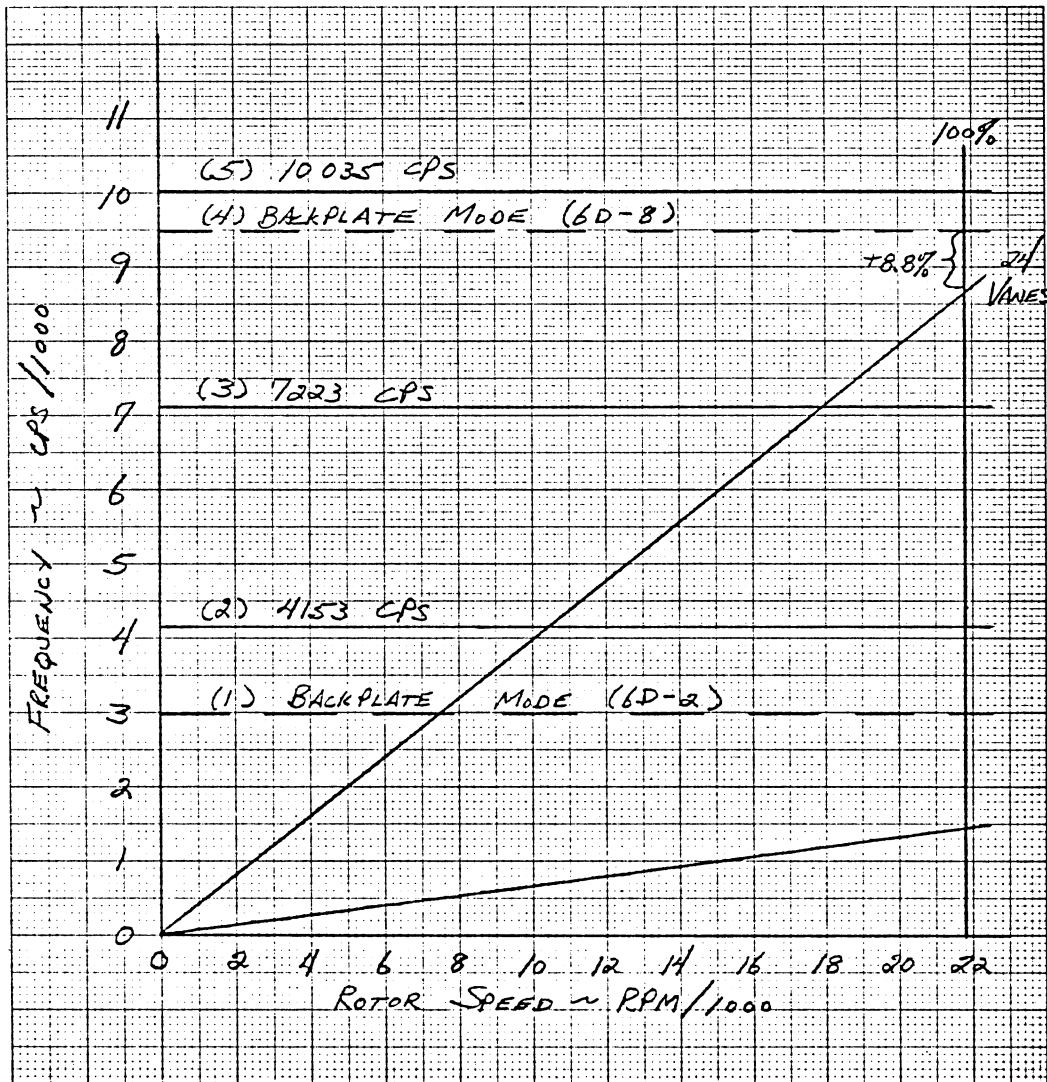


Figure 54. Frequency-Speed Diagram for Splitter Blade of Scaled Impeller.

(2E0) and its second harmonic, 4E0. The second and eighth modes shown in Figure 53 are backplate modes. The remaining modes are essentially blade modes with little or no coupling to the backplate structure.

The sixth diametral mode pattern (6D) was selected for analysis of the blade/backplate system because it is the only candidate mode which can be excited by the 24 engine order (diffuser vane number) when there are 30 airfoils on the rotating disk. The first backplate mode (6D-2), Figure 53, is acceptable because it is in resonance with 24E0 at a very low speed and should be exposed to excitation only during transient operation. The second backplate mode (6D-8) should not be of concern unless steady state operation near 109% mechanical speed is anticipated.

In general, the natural frequencies are similar to those of the 404-III and, therefore, should be totally acceptable for anticipated rig operation.

IV. MANUFACTURING DEFINITION OF SCALED IMPELLER

This section describes the procedure by which the "hot running" impeller is converted into the "cold" or manufacturing definition. The initial portion of this process is to combine the "hot running" impeller geometry defined by aerodynamics with the deflection characteristics calculated in the static stress analysis.

The "hot to cold" static stress analysis is performed by iteratively adjusting the impeller geometry and analytically "spinning" this geometry to design speed and temperature. Convergence is assumed when this "hot running" geometry matches that originally defined by the aerodynamics group. The final output of this analysis is a full 3-D cartesian definition which gives the X, Y, Z location of the desired "hot running" blade and the ∇X , ∇Y , ∇Z deflection required to convert this "hot running" blade to the manufacturing definition.

Blade generation programs, then, apply these deflections, reconstruct the "cold" blade, modify the shroud contour for the desired "hot running" clearance and, finally, define the cold blade on a series of planes passed both parallel and perpendicular to the engine axis.

Figure 55 indicates DDA practice for applying the "hot running" clearance. A constant clearance is first subtracted from the "hot" shroud line defined previously in Table II. The original 404-III had a constant 0.010 inches removed from the impeller^{hot} shroud line. Using the 1.6529 linear scale factor, a clearance of .016529^{*} was used for the scaled impeller. Since a static structure analysis was not performed, an absolute definition of the required "cold" build clearance is not possible. However, the change in clearance (relative to the originally defined "hot" shroud line) calculated for the impeller is provided in Figure 56 for reference.

* CHANGED TO .008" HOT CLEARANCE 7/12/83

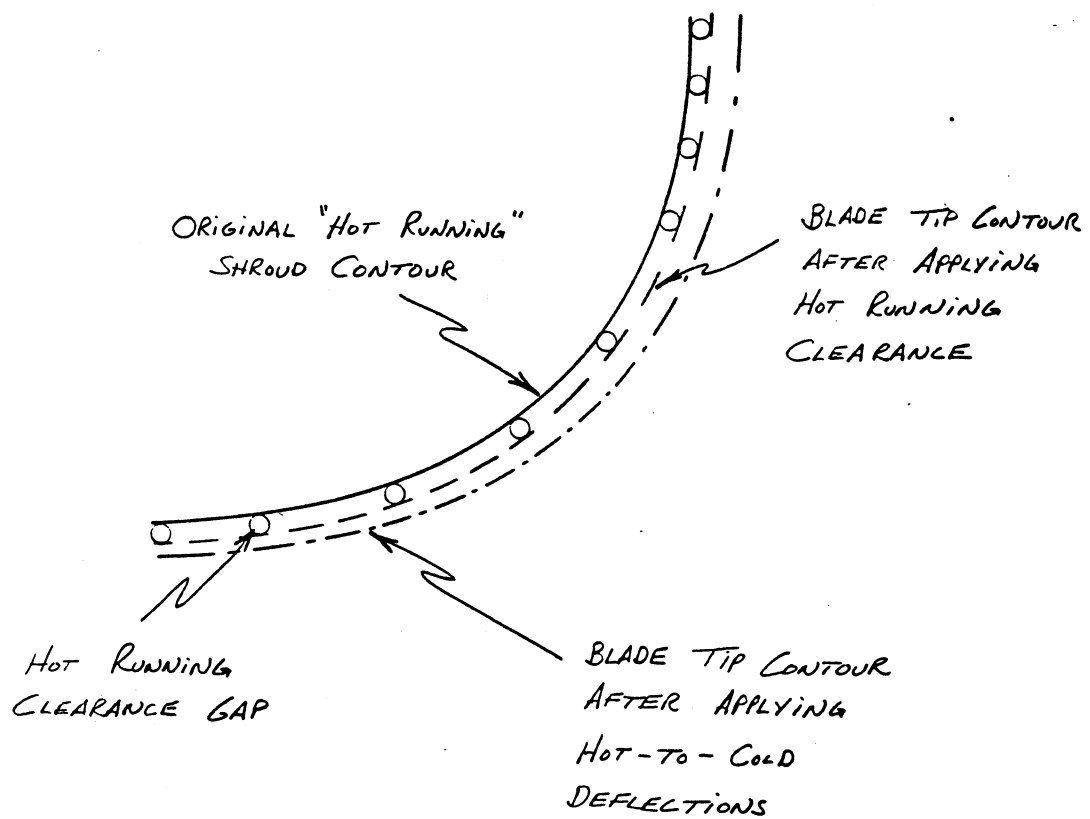


Figure 55. DDA Procedure for Clearance Allowance.

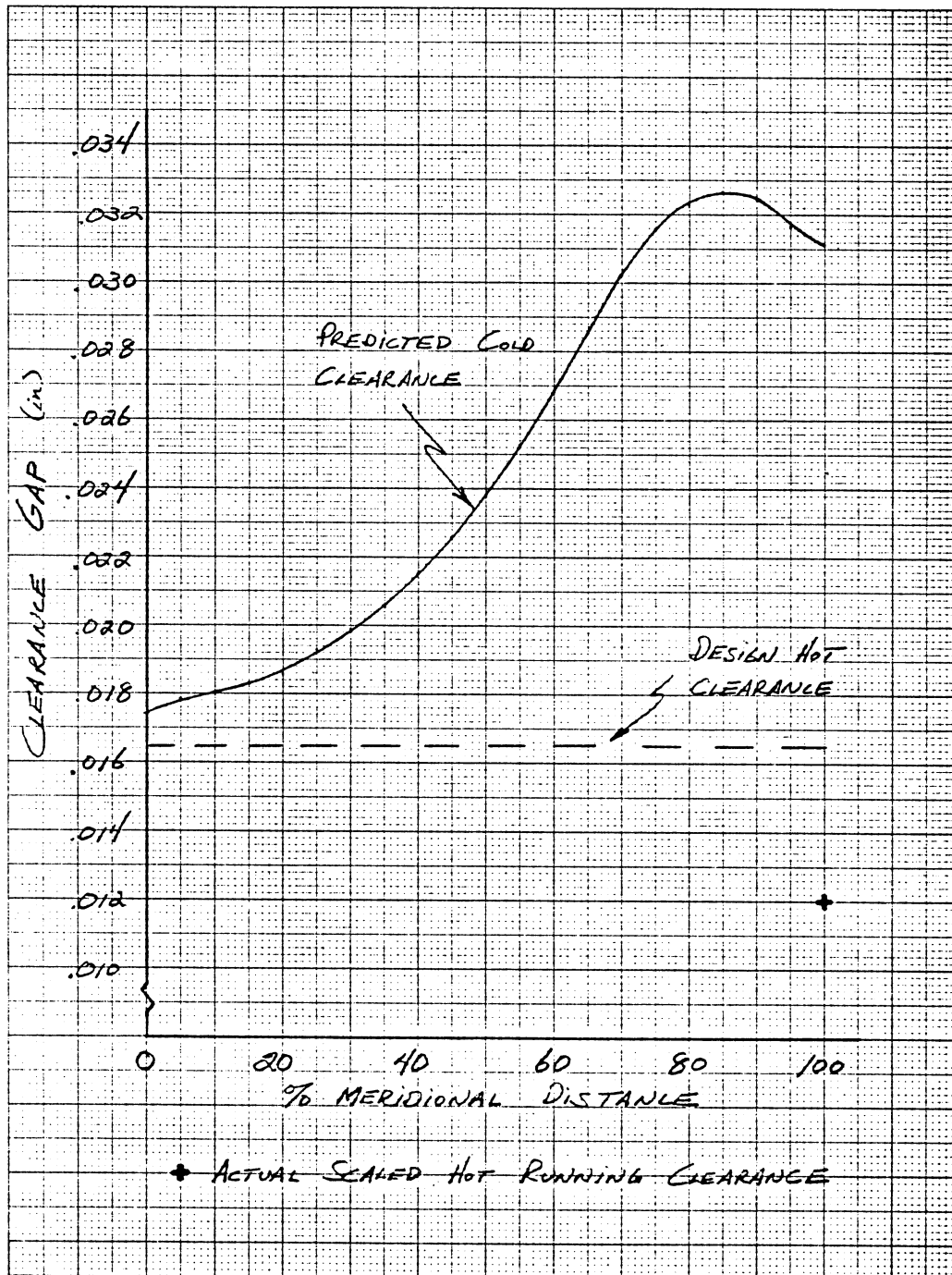


Figure 56. Scaled Impeller Clearance Change from "cold build" to "hot running" Condition.

The final "cold, manufacturing" definition of the impeller blade and splitter with the 0.016529 inch clearance removed is given in Tables V and VI, respectively. The "cold" blade surfaces are assumed to be constructed by straight lines from the hub to the shroud along the defined quasi-normals. The splitter blades are equally spaced between full blades at the impeller exit.

Planar sections were then passed through this "cold" geometry. The printed coordinate intersections of these planes with the quasi-normals is called a blade book and is included as Attachment A. Punched card definition of the hot and cold blade surfaces defined in Tables II, III, V and VI and the blade book coordinates are included as Attachment B. Milar plots of the planar intersections are known as Master Charts and are included as Attachment C. These plots are five times scale and can be used for final part inspection. Finally, a SK drawing was prepared to define the wheel geometry and locations of the planar Master Chart sections. This drawing is Attachment D.

MEAN BLADE DEFINITION - FULL BLADE.

% N/A	RUE	FUE	SHR CUL	Z	THAN	THETA	THETA	THETA
	HUB	HUB	HUB	SHROUD	HUB	SHROUD	HUB	SHROUD
0.0000	1.2326	0.9744	1.4899	0.012	1324	0.759	1.6331	0.0319
0.0000	1.1604	0.9388	1.4355	0.018	1340	0.737	1.6000	0.0387
0.0000	1.0944	0.9032	1.3811	0.025	1356	0.715	1.5657	0.0455
0.0000	1.0344	0.8676	1.3267	0.031	1372	0.693	1.5314	0.0523
0.0000	0.9744	0.8320	1.2723	0.038	1388	0.671	1.4971	0.0591
0.0000	0.9144	0.7964	1.2179	0.044	1404	0.649	1.4628	0.0659
0.0000	0.8544	0.7608	1.1635	0.051	1420	0.627	1.4285	0.0727
0.0000	0.7944	0.7252	1.1091	0.057	1436	0.605	1.3942	0.0795
0.0000	0.7344	0.6896	1.0547	0.064	1452	0.583	1.3599	0.0863
0.0000	0.6744	0.6540	1.0003	0.070	1468	0.561	1.3256	0.0931
0.0000	0.6144	0.6184	0.9459	0.077	1484	0.539	1.2913	0.0999
0.0000	0.5544	0.5828	0.8915	0.083	1500	0.517	1.2570	0.1067
0.0000	0.4944	0.5472	0.8371	0.090	1516	0.495	1.2227	0.1135
0.0000	0.4344	0.5116	0.7827	0.096	1532	0.473	1.1884	0.1203
0.0000	0.3744	0.4760	0.7283	0.103	1548	0.451	1.1541	0.1271
0.0000	0.3144	0.4404	0.6739	0.109	1564	0.429	1.1198	0.1339
0.0000	0.2544	0.4048	0.6195	0.116	1580	0.407	1.0855	0.1407
0.0000	0.1944	0.3692	0.5651	0.122	1596	0.385	1.0512	0.1475
0.0000	0.1344	0.3336	0.5107	0.129	1612	0.363	1.0169	0.1543
0.0000	0.0744	0.2980	0.4563	0.135	1628	0.341	0.9826	0.1611
0.0000	0.0144	0.2624	0.4019	0.142	1644	0.319	0.9483	0.1679
0.0000	0.0000	0.2268	0.3475	0.148	1660	0.297	0.9140	0.1747
0.0000	0.0000	0.1912	0.2931	0.155	1676	0.275	0.8797	0.1815
0.0000	0.0000	0.1556	0.2387	0.161	1692	0.253	0.8454	0.1883
0.0000	0.0000	0.1200	0.1843	0.168	1708	0.231	0.8111	0.1951
0.0000	0.0000	0.0844	0.1299	0.174	1724	0.209	0.7768	0.2019
0.0000	0.0000	0.0488	0.0755	0.181	1740	0.187	0.7425	0.2087
0.0000	0.0000	0.0132	0.0211	0.187	1756	0.165	0.7082	0.2155
0.0000	0.0000	0.0000	0.0000	0.194	1772	0.143	0.6739	0.2223
0.0000	0.0000	0.0000	0.0000	0.200	1788	0.121	0.6396	0.2291
0.0000	0.0000	0.0000	0.0000	0.207	1804	0.099	0.6053	0.2359
0.0000	0.0000	0.0000	0.0000	0.213	1820	0.077	0.5710	0.2427
0.0000	0.0000	0.0000	0.0000	0.220	1836	0.055	0.5367	0.2495
0.0000	0.0000	0.0000	0.0000	0.226	1852	0.033	0.5024	0.2563
0.0000	0.0000	0.0000	0.0000	0.233	1868	0.011	0.4681	0.2631
0.0000	0.0000	0.0000	0.0000	0.240	1884	0.000	0.4338	0.2699
0.0000	0.0000	0.0000	0.0000	0.246	1900	0.000	0.3995	0.2767
0.0000	0.0000	0.0000	0.0000	0.253	1916	0.000	0.3652	0.2835
0.0000	0.0000	0.0000	0.0000	0.259	1932	0.000	0.3309	0.2903
0.0000	0.0000	0.0000	0.0000	0.266	1948	0.000	0.2966	0.2971
0.0000	0.0000	0.0000	0.0000	0.272	1964	0.000	0.2623	0.3039
0.0000	0.0000	0.0000	0.0000	0.279	1980	0.000	0.2280	0.3107
0.0000	0.0000	0.0000	0.0000	0.285	1996	0.000	0.1937	0.3175
0.0000	0.0000	0.0000	0.0000	0.292	2012	0.000	0.1594	0.3243
0.0000	0.0000	0.0000	0.0000	0.298	2028	0.000	0.1251	0.3311
0.0000	0.0000	0.0000	0.0000	0.305	2044	0.000	0.0908	0.3379
0.0000	0.0000	0.0000	0.0000	0.311	2060	0.000	0.0565	0.3447
0.0000	0.0000	0.0000	0.0000	0.318	2076	0.000	0.0222	0.3515
0.0000	0.0000	0.0000	0.0000	0.324	2092	0.000	0.0000	0.3583
0.0000	0.0000	0.0000	0.0000	0.331	2108	0.000	0.0000	0.3651
0.0000	0.0000	0.0000	0.0000	0.337	2124	0.000	0.0000	0.3719
0.0000	0.0000	0.0000	0.0000	0.344	2140	0.000	0.0000	0.3787
0.0000	0.0000	0.0000	0.0000	0.350	2156	0.000	0.0000	0.3855
0.0000	0.0000	0.0000	0.0000	0.357	2172	0.000	0.0000	0.3923
0.0000	0.0000	0.0000	0.0000	0.363	2188	0.000	0.0000	0.3991
0.0000	0.0000	0.0000	0.0000	0.370	2204	0.000	0.0000	0.4059
0.0000	0.0000	0.0000	0.0000	0.376	2220	0.000	0.0000	0.4127
0.0000	0.0000	0.0000	0.0000	0.383	2236	0.000	0.0000	0.4195
0.0000	0.0000	0.0000	0.0000	0.389	2252	0.000	0.0000	0.4263
0.0000	0.0000	0.0000	0.0000	0.396	2268	0.000	0.0000	0.4331
0.0000	0.0000	0.0000	0.0000	0.402	2284	0.000	0.0000	0.4399
0.0000	0.0000	0.0000	0.0000	0.409	2300	0.000	0.0000	0.4467
0.0000	0.0000	0.0000	0.0000	0.415	2316	0.000	0.0000	0.4535
0.0000	0.0000	0.0000	0.0000	0.422	2332	0.000	0.0000	0.4603
0.0000	0.0000	0.0000	0.0000	0.428	2348	0.000	0.0000	0.4671
0.0000	0.0000	0.0000	0.0000	0.435	2364	0.000	0.0000	0.4739
0.0000	0.0000	0.0000	0.0000	0.441	2380	0.000	0.0000	0.4807
0.0000	0.0000	0.0000	0.0000	0.448	2396	0.000	0.0000	0.4875
0.0000	0.0000	0.0000	0.0000	0.454	2412	0.000	0.0000	0.4943
0.0000	0.0000	0.0000	0.0000	0.461	2428	0.000	0.0000	0.5011
0.0000	0.0000	0.0000	0.0000	0.467	2444	0.000	0.0000	0.5079
0.0000	0.0000	0.0000	0.0000	0.474	2460	0.000	0.0000	0.5147
0.0000	0.0000	0.0000	0.0000	0.480	2476	0.000	0.0000	0.5215
0.0000	0.0000	0.0000	0.0000	0.487	2492	0.000	0.0000	0.5283
0.0000	0.0000	0.0000	0.0000	0.493	2508	0.000	0.0000	0.5351
0.0000	0.0000	0.0000	0.0000	0.500	2524	0.000	0.0000	0.5419
0.0000	0.0000	0.0000	0.0000	0.506	2540	0.000	0.0000	0.5487
0.0000	0.0000	0.0000	0.0000	0.513	2556	0.000	0.0000	0.5555
0.0000	0.0000	0.0000	0.0000	0.519	2572	0.000	0.0000	0.5623
0.0000	0.0000	0.0000	0.0000	0.526	2588	0.000	0.0000	0.5691
0.0000	0.0000	0.0000	0.0000	0.532	2604	0.000	0.0000	0.5759
0.0000	0.0000	0.0000	0.0000	0.539	2620	0.000	0.0000	0.5827
0.0000	0.0000	0.0000	0.0000	0.545	2636	0.000	0.0000	0.5895
0.0000	0.0000	0.0000	0.0000	0.552	2652	0.000	0.0000	0.5963
0.0000	0.0000	0.0000	0.0000	0.558	2668	0.000	0.0000	0.6031
0.0000	0.0000	0.0000	0.0000	0.565	2684	0.000	0.0000	0.6099
0.0000	0.0000	0.0000	0.0000	0.571	2700	0.000	0.0000	0.6167
0.0000	0.0000	0.0000	0.0000	0.578	2716	0.000	0.0000	0.6235
0.0000	0.0000	0.0000	0.0000	0.584	2732	0.000	0.0000	0.6303
0.0000	0.0000	0.0000	0.0000	0.591	2748	0.000	0.0000	0.6371
0.0000	0.0000	0.0000	0.0000	0.597	2764	0.000	0.0000	0.6439
0.0000	0.0000	0.0000	0.0000	0.604	2780	0.000	0.0000	0.6507
0.0000	0.0000	0.0000	0.0000	0.610	2796	0.000	0.0000	0.6575
0.0000	0.0000	0.0000	0.0000	0.617	2812	0.000	0.0000	0.6643
0.0000	0.0000	0.0000	0.0000	0.623	2828	0.000	0.0000	0.6711
0.0000	0.0000	0.0000	0.0000	0.630	2844	0.000	0.0000	0.6779
0.0000	0.0000	0.0000	0.0000	0.636	2860	0.000	0.0000	0.6847
0.0000	0.0000	0.0000	0.0000	0.643	2876	0.000	0.0000	0.6915
0.0000	0.0000	0.0000	0.0000	0.649	2892	0.000	0.0000	0.6983
0.0000	0.0000	0.0000	0.0000	0.656	2908	0.000	0.0000	0.7051
0.0000	0.0000	0.0000	0.0000	0.662	2924	0.000	0.0000	0.7119
0.0000	0.0000	0.0000	0.0000	0.669	2940	0.000	0.0000	0.7187
0.0000	0.0000	0.0000	0.0000	0.675	2956	0.000	0.0000	0.7255
0.0000	0.0000	0.0000	0.0000	0.682	2972	0.000	0.0000	0.7323
0.0000	0.0000	0.0000	0.0000	0.688	2988	0.000	0.0000	0.7391
0.0000	0.0000	0.0000	0.0000	0.695	3004	0.000	0.0000	0.7459
0.0000	0.0000	0.0000	0.0000	0.701	3020	0.000	0.0000	0.7527
0.0000	0.0000	0.0000	0.0000	0.708	3036	0.000	0.0000	0.7595
0.0000	0.0000	0.0000	0.0000	0.714	3052	0.000	0.0000	0.7663
0.0000	0.0000	0.0000	0.0000	0.721	3068	0.000	0.0000	0.7731
0.0000	0.0000	0.0000	0.0000	0.727	3084	0.000	0.0000	0.7799
0.0000	0.0000	0.0000	0.0000	0.734	3100	0.000	0.0000	0.7867
0.0000	0.0000	0.0000	0.0000	0.740	3116	0.000	0.0000	0.7935
0.0000	0.0000	0.0000	0.0000	0.747	3132	0.000	0.0000	0.8003
0.0000	0.0000	0.0000	0.0000	0.753	3148	0.000	0.0000	0.8071
0.0000	0.0000	0.0000	0.0000	0.760	3164	0.000	0.0000	0.8139
0.0000	0.0000	0.0000	0.0000	0.766	3180	0.000	0.0000	0.8207
0.0000	0.0000	0.0000	0.0000	0.773	3196	0.000	0.0000	0.8275
0.0000	0.0000	0.0000	0.0000	0.779	3212	0.000	0.0000	0.8343
0.0000	0.0000	0.0000	0.0000	0.786	3228	0.000	0.0000	0.8411
0.0000	0.0000	0.0000	0.0000	0.792	3244	0.000	0.0000	0.8479
0.0000	0.0000	0.0000	0.0000	0.799	3260	0.000	0.0000	0.8547
0.0000	0.0000	0.0000	0.0000	0.805	3276	0.000	0.0000	0.8615
0.0000	0.0000	0.0000	0.0000	0.812	3292	0.000	0	

TABLE VI. SCALED 4C4-III IMPELLER COORDINATES - COLD BLADE.
MEAN BLADE DEFINITION - SPLITTER.

[illegible]

V. APPENDICIES

Attachment A Impeller Blade Book (not attached directly to this report)

Attachment B Punched Card Definition of "Hot" and "Cold" Blade Surfaces (not attached directly to this report)

Attachment C Milar Plots of Master Chart Sections (not attached directly to this report)

Attachment D Impeller Detail Drawing (page 73)



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